A CLIMATIC RECORD FOR SOUTH-EAST SCOTLAND AND ITS IMPLICATIONS FOR AGRICULTURE AND DISEASE

KIRSTY DUNCAN

DOCTOR OF PHILOSOPHY

UNIVERSITY OF EDINBURGH

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To my Parents.

Helen and Errol Duncan

To my Husband.

Dr. Sean Godfrey

ABSTRACT

A mean monthly temperature record is reconstructed for 50-year periods for Edinburgh, in the millenium 800-1900 AD. The development of a reliable record of past climate for Edinburgh and south-east Scotland permits the study of the significance of past climatic change on humans in these regions.

First, the possible influence of climate on agriculture is investigated over the last 800 years. Specifically, a replication study of M.L. Parry's (1972) classic thesis, 'Changes in the Upper Limit of Cultivation in South-East Scotland: 1600-1900 AD', is undertaken. Second, the possible influence of climate on disease is investigated. The diseases covered include the bubonic plague, malaria, and ergotism.

Finally, the new mean monthly temperature record for Edinburgh is used as an historical analogue for possible greenhouse-gas induced warming in south-east Scotland. Because the record is sufficiently detailed, the possible influence of the predicted warming on agriculture and two communicable diseases, namely Lyme disease and Leptospirosis, is investigated.

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CHAPTER 1: INTRODUCTION

CLIMATE AND ITS EFFECT ON HUMANKIND

This thesis aims to study the possible influence of climate on human affairs. The impact of climatic fluctuations has long been recognized as one of the factors that requires consideration in analysing the course of economic, social and political change in past time. However, there has always been dispute about just how much attention needs to be paid to this variable.

The majority of historians have been largely content to ignore climate (Saltmarsh 1941; Hoskins et al., 1952; Slicher Van Bath 1963; Hoskins 1964; Beresford 1969; Brandon 1969; Smout 1969 and Ingram et al. 1981). It is, however, generally accepted by a small number of historians, most archaeologists and earth scientists that climate is an important independent variable affecting human societies.

In the early twentieth century Huntington (1907, 1915) described climate as all-pervasive in moulding social structure, settlement patterns and human behaviour. These generalised and oversimplified deterministic views later fell into disfavour amongst social scientists. However, occasionally, climatic determinism re-emerges in contemporary thought (Riebsame 1985). For example, Harrison (1979) attributed a range of sociotechnical characteristics to global climate.

Climatic determinism, as viewed by Pearson (1978), does not necessarily imply a belief that the course of history is explicable in terms of climate, as suggested by Huntington. Rather, Pearson suggests that climatic factors have been among the most important influences on the development of civilizations. Such a view is held, for example, by Lamb (1969), Chappell (1970) and Bryson et al. (1977). Others have noted the importance of climatic factors in particular areas and periods. These include Utterstrom (1955), Braudel (1973) and Parker (1979).

Although researchers largely agree that climate is an important independent variable affecting human societies, they disagree on the timescale on which the impact occurs. Historians, archaeologists and earth scientists generally agree that short-term (intra-annual, annual and inter-annual) variations in weather have immediate impacts on harvests and other economic activities (Le Roy Ladurie 1972; Braudel 1973 and de Vries 1980).

More recently, a number of studies have focused attention on the influence of medium-term variations of weather on human societies. These variations include, for example, clusters of extreme seasons or years (Pfister 1981). Post (1980) suggested that pre-industrial peoples may have adjusted to annual fluctuations. However, after a succession of severe years, in terms of weather, the systems of adjustment would have been over-challenged: this would have lead to higher death rates and a decline in economic activity.

Long-term climate of decades or centuries has also been used, as an important independent variable, to explain the course of human history. Utterstrom (1955), for example, suggested that climatic changes may have influenced population movements in medieval and early modern Europe. Braudel (1973) stressed that all of Europe in the early 16th century was favoured by climate. Parry (1975) suggested that reclamation and reversion of farmland in south-east Scotland could, in part, be explained by long-term shifts in climate. More recently, Parker (1979) has linked the crisis in the economy and society of seventeenth-century Europe with climatic deterioration.

The possible influence of long-term climate on humankind has provoked both scepticism and criticism, on several accounts. Early theories linking climatic change with economic cycles (Beveridge 1921) were discredited by the initial climatic work of Britton (1937) and Brooks (1949). Subsequently, Britton's chronology has been superseded and corrected by Lamb (1966). Lamb (1966) showed that economic trends did, in fact, correlate with his own climate record. Furthermore, Brooks' studies were largely concerned with rainfall variations and paid little attention to the equally important factor of temperature.

Another view is that the magnitude of past long-term changes in climate, though striking from a scientific point of view, has been too small to warrant consideration as a variable capable of influencing human societies. Le Roy Ladurie (1972), for example, questioned whether a 1°C difference in mean temperature over the last millenium could have had any influence on human society.

A final viewpoint is that the lack of detailed information on past weather and climate, human affairs and poor understanding of the complex climate-human relationships prevent any serious study of the subject (Ingram et al. 1981). Climate impact studies often require very detailed information about individual seasons, months or even weeks. Unfortunately, such data are often absent or sparse for large regions of the world (Bradley 1985). Data on human activities are also highly variable both in quality and quantity (Kates 1985). As a result, all attempts to identify climate-human interactions depend on relatively simple assumptions.

CLIMATE IMPACT ASSESSMENT

The study of the possible impact of climate on humankind requires the understanding of three basic elements: climatic events, exposure units and impacts.

Climatic events may be short-term, medium-term or long-term. Past climate has been successfully derived from such proxy records as:

(1) historical records, such as Lamb's (1977) decadal winter severity and summer wetness indices;

(2) oxygen isotope measurements (Dansgaard et al. 1975; Schwartz et al. 1991);

(3) periglacial features (Washburn 1979, 1980);

(4) isotopic variations in speleothems (Duplessy et al. 1970; Talma et al. 1992);

(5) arctic treeline fluctuations (Nichols 1967; Moser et al. 1991);

(6) alpine treeline fluctuations (Karlen 1976);

(7) insect remains (Coope 1977; Elias et al. 1990);

(8) palynological reconstructions (Nichols 1975; Clarke et al. 1990);

(9) isotope dendroclimatology (Schweingruber et al. 1978; Luckman et al., 1990); and

(10) ring-width dendroclimatology (La Marche 1974; Graumlich et al., 1986).

For a complete listing of methods used in the reconstruction of past climates, see Bradley (1985).

GLOSSARY

Exposure units refer to: (1) individuals, populations or species; (2) activities or livelihoods; (3) specific sectors; (4) or both the groups and activities found within a specific society, region or nation which are exposed to climatic events.

Impacts refer to the consequences of the exposure to specific climatic events. It is useful to distinguish between first-order impacts which are usually of a bio-physical nature and higher-order impacts which consist of socio-economic evaluation (Kates 1985). Reliability is greatest for first-order impacts. This is because more is known about bio-physical impacts; less is known about long-term social or economic change. First-order impact studies include studies of agriculture (Nix 1985), fisheries (Kawasaki 1985), pastorialism (Houerou 1985) and energy resources (Novaky et al. 1985). Higher-order impact studies include studies of health, nutrition and human development (Escudero 1985), economy (Knox-Lovell et al., 1985) and society (Farhar-Pilgrim 1985).

THESIS STRUCTURE

This thesis, as previously stated, aims to study the possible influence of climate on humankind. It draws upon the theories, methods and research findings from a number of disciplines including meteorology, climatology, dendroclimatology, Scottish ethnology, agrometeorology, archaeology, palynology, history, medical history and medicine.

Specifically, this thesis examines the relationship between long-term, medium-term and short-term climate change and people in south-east Scotland and Scotland as a whole, in the past and in the future. A number of case studies on climatic impact are presented. These examine the possible influence of: (1) past climate on agriculture; (2) past climate on disease; (3) future climate on agriculture and (4) future climate on disease.

To examine the relationship between climate and people, it is first necessary to establish a reliable record of climatic changes and fluctuations. This is achieved in Chapter Two by a reconstruction of a mean monthly temperature record for 50-year periods for Edinburgh, in the millenium 800-1900 AD. This record is new and is the most detailed reconstruction derived for north Britain. It demonstrates long-term and secular climate change. Given this record, it is possible to calculate temperatures and long-term trends for other regions of Scotland. From 1659-1763 AD, annual temperatures are available and from 1764-1896 AD, seasonal temperatures are available for Edinburgh. These last two records are of sufficient detail to allow a study of short-term and medium-term climatic changes.

Chapter Three examines the influence of secular climatic change on historical agriculture, in south-east Scotland. Specifically, this chapter is a replication study and a re-evaluation of M.L. Parry's (1972) major work 'Changes in the Upper Limit of Cultivation in South-East Scotland', which shed valuable light on the link between climatic change and agriculture. A replication study of Parry's pioneering and important work seems necessary because: (1) more information is now available; and (2) problems exist in the original study.

A clarification of the term replication seems necessary because of the widespread confusion which exists about its meaning. Replication is said to occur if: (1) an experiment is repeated by another researcher with approximately similar significant results; (2) an experiment is repeated day after day with significant agreement or (3) the essential nature or essential feature of the experiment is reproduced by a number of people working in different places (Morris 1980; Collins 1985).

Replication is defined in this thesis as meaning a general conceptual replication, in which an attempt is made to replicate the general features of another's work. This approach follows Morris (1980), who stated that complete repeatability is not necessary because new information can be generated with partial replication.

Replication is important because it is central to the scientific method (Bell 1974). This is because (1) only by replication can we convince ourselves that we are not dealing with merely isolated coincidence, but with events which on account of their regularity and reproducibility are, in fact, truly related (Collins 1985); and (2) proven repeatability allows us to build upon our own past research and that carried out by others. Diversity of design and personnel are important because confirmatory power seems to increase as the differences in construction between a confirming experiment and the original experiment increase (Collins 1985).

Hence, this work aims firstly to assess Parry's finding that the agricultural limit does shift in relation to climatic change, and secondly to provide a new, refined methodology for calculating accumulated warmth for the growing season. The climatic reconstructions are covered in Chapter Two and the correlation with any shift in the cultivation limit in Chapter Three.

Chapter Four examines the relationship between climate and past outbreaks of disease in Scotland. The effects of climate on disease in the past have been studied by only a limited number of researchers (Ogilvie 1981; Post 1983a and 1983b and Pfister 1984). In this thesis, the role of climate as a possible factor in the spread of bubonic plague, malaria, ergotism and the Scottish witch-hunts is considered. Plague is linked to secular climatic change, malaria to secular, medium-term and short-term climatic change and ergotism and the Scottish witch-hunts to medium-term climatic variations.

Chapter Five uses the new mean monthly temperature record established for Edinburgh (Chapter Two), as an historical analogue for possible greenhouse-gas induced warming (secular climatic change) in south-east Scotland. This new approach opens up the possibility of effective prediction of climate at the regional level.

The record is of sufficient detail to link the effects of the predicted change with two communicable diseases, namely Lyme Disease and leptospirosis. This, again, is a very new study area (Aitken 1991). The literature on climatic impacts upon health has usually concentrated on the immediate effects: such as sunburn, heatstroke, heat cramps, changes in sleep patterns, frostbite and drowning. For a thorough review of the literature, see Landsberg (1984). Population behaviour has also been linked with climatic changes (Escudero 1985). For example, political upheaval and migration have been explored in relation to CO_2-induced climatic warming (Rotberg et al. 1981). And finally, the climatic impacts on diet and nutrition have been studied. For example, Chambers (1981) has examined seasonality and its effect on human suffering, illness and death.

Chapter Six summarizes the conclusions from the thesis and outlines work for future research.

CHAPTER 2: THE CLIMATIC RECORD FOR SOUTH-EAST SCOTLAND

INTRODUCTION

This chapter reconstructs climate for Edinburgh and south-east Scotland for the period 800-1900 AD. In this thesis, south-east Scotland refers to the Scottish counties of Midlothian, East Lothian, Berwickshire, Roxburghshire and Selkirkshire'. This chronology of secular change is the most reliable available, since it has been adjusted to be representative of Edinburgh and it has monthly values which are calibrated with an instrumental record for Edinburgh. The record is intended as a basis for: (1) subsequent discussion of the significance of past changes in climate on agriculture and the occurrence of communicable disease; and (2) an historical analogue for possible greenhouse-gas induced warming in south-east Scotland.

TEMPERATURE

Today, there exist only two comprehensive instrumental temperature sets for all of Great Britain: that of Manley (1974) for central England in the years 1659-1973 and that of Mossman (1896) for Edinburgh in the years 1764-1896.

In the past, much use has been made of the English data to extrapolate past climatic trends into Scotland. Doubts have been expressed over the use of English records, particularly with respect to the study of climatic change in Scotland (Parry 1972). For example, Price (1987) states that, 'The central England temperature for the past few centuries is representative of central England and less so of Scotland'. If present-day records for 1951-1980 are analysed, it is apparent that London is, on average, almost 1°C warmer than Edinburgh (The Meteorological Office 1989). If the present is the key to the past, this would suggest that a similar difference existed in the past. If such a difference did exist, it would be erroneous to use English records for establishing past records in Scotland.

It has been demonstrated by Duncan (1991) that if central England temperatures are employed to establish the start of the growing season in Scotland, the proposed date would actually be too early. Using a base temperature for growth of 4.4°C, the growing season utilizing English data begins as early as 15th February; whereas the growing season using Scottish data may not begin until 22nd February. Using a base temperature for growth of 6.0°C, the growing season based on English data commences on March 17th; while the Scottish equivalent starts on 3rd April - a difference of two and a-half weeks. Furthermore, Duncan (1991) has shown that if central England data is employed to determine the height of any agricultural limit, the figure overestimates the actual altitude by 66m.

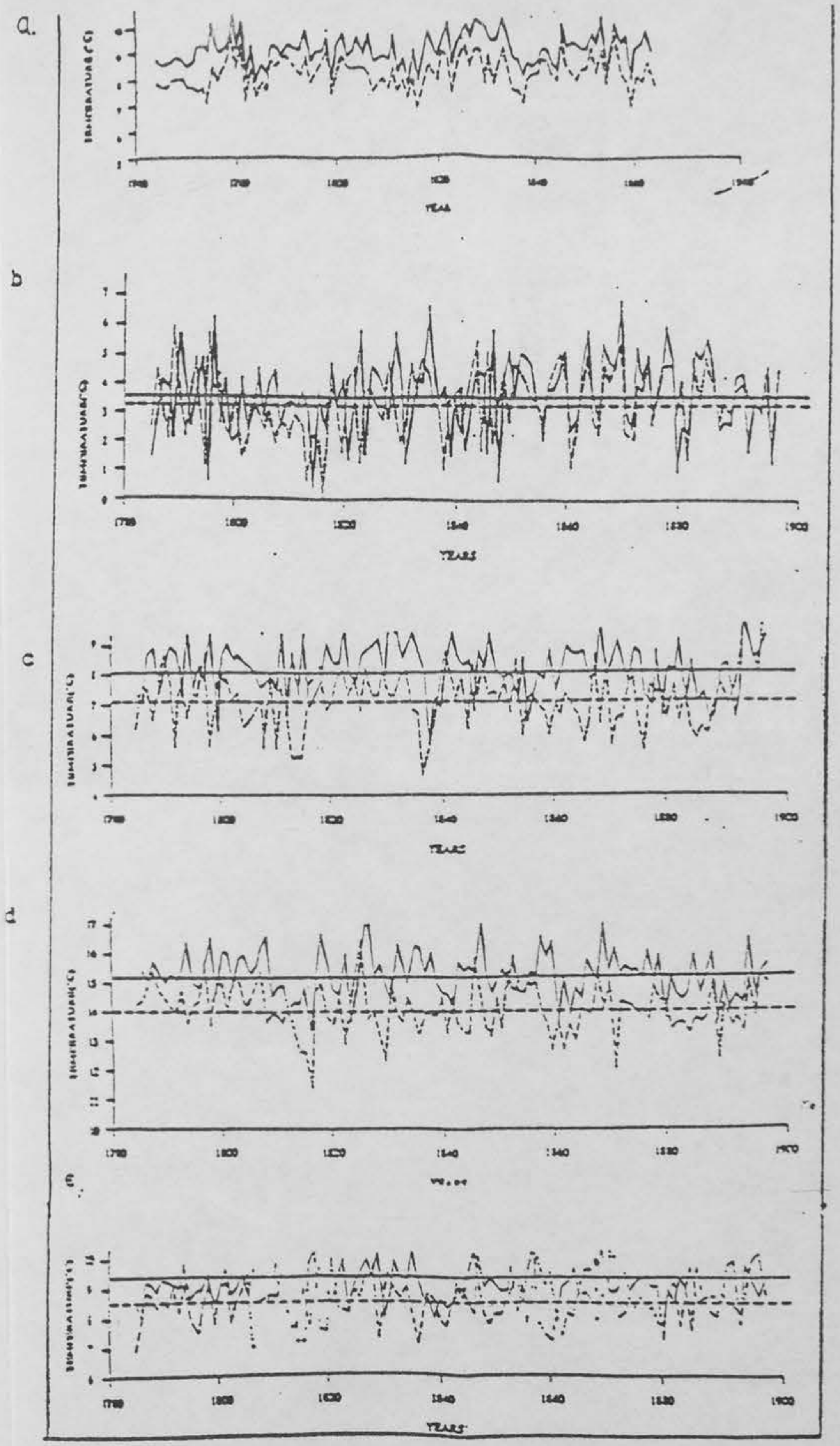
In light of the expressed doubts it seems useful to reconstruct a Scottish temperature record. As a first step, a critical comparison of Manley's and Mossman's records was undertaken in order to determine if the English and Scottish data differed significantly. This fulfills a long-standing need for a comparison between the English and Scottish temperature records (Lamb pers. comm. (1990).

COMPARABILITY OF THE EXISTING ANNUAL TEMPERATURE RECORDS

Figure 2.1 and Table 2.1 show a comparison of the two data sets, both in terms of mean annual temperature and seasonal temperature. A notable feature is the difference in mean annual temperature between the two temperature series. The mean temperature of central England is 9.1°C, whereas the average temperature of Edinburgh is 8.3°C.

Also noteworthy, is the degree of agreement between the two temperature series. As Manley (1953) stated: 'even the short-term anomalies of temperature found in the English Midland data are also available in Mossman's series for Edinburgh'. The correlation coefficient, or r value, for the two series is 0.80. This result is significantly different from 0 at the $p=0.001$ level.

Extreme values were considered in order to assess further the similarity of the two series. Table 2.2 shows the method used in analysing the extreme values. First, the mean ($\bar{x}$) and the standard deviation SD, were calculated for each data set. Second, an extreme value, $\bar{x}$ + 1.5 SD, was chosen. Since temperature is almost normally distributed, the choice of an extreme value is fairly arbitrary. Thus, the values of $\bar{x}$ + 2 or 3 SD could have been used. Third, each year that exceeded either $\bar{x}$ +1.5 SD for warm years or $\bar{x}$ - 1.5 SD for cold years was identified. Table 2.2 demonstrates that there is agreement between the two data sets with warm or cold years, common to both locations. The relationship is, however, stronger in one direction. That is, if Edinburgh had a warm year, so too did England; whereas, an English warm year was not necessarily matched in Scotland.



2.1 a Mean Annual Temperature for Central England and Edinburgh

b Mean Winter Temperature (D,JF) for Central England and Edinburgh

c Mean Spring Temperature (M,AM) for Central England and Edinburgh

d Mean Summer Temperature (J,JA) for Central England and Edinburgh

e Mean Autumn Temperature (S,ON) for Central England and Edinburgh

Table 2.1

A Comparison of the Seasonal and Annual Temperatures ($^{\circ}C$) of Edinburgh and Central England

	Annual	Winter	Spring	Summer	Autumn
Central England	9.1	3.6	8.1	15.2	9.4
Edinburgh	8.3	3.3	7.2	14.1	8.6
Mean Difference	0.8	0.3	0.9	1.1	0.8
Difference Between the Annual and Seasonal Mean Difference		-0.5	+0.1	+0.3	0.0

Table 2.2

Extreme Values

	$\bar{X}$ Temp.	SD	$\bar{X}$+1.5 SD	$\bar{X}$-1.5 SD
Central England	9.0968	.6226	10.0307	8.1629

Years Whose Mean Annual Temperature is > $\bar{X}$+1.5 SD

1775, 1779, 1781, 1822, 1826, 1828, 1831, 1834, 1846, 1857, 1869

Years Whose Mean Annual Temperature is < $\bar{X}$-1.5 SD

1782, 1799, 1814, 1816, 1838, 1855

	$\bar{X}$ Temp.	SD	$\bar{X}$+1.5 SD	$\bar{X}$-1.5 SD
Edin-burgh	8.2878	.6099	9.2026	7.3729

Years Whose Mean Annual Temperature is > $\bar{X}$+1.5 SD

1779, 1781, 1826, 1834, 1846, 1852, 1857, 1868, 1893

-seven years common with central England

Years Whose Mean Annual Temperature < $\bar{X}$-1.5 SD

1782, 1814, 1829, 1838

-three years common with Central England

There are interesting seasonal contrasts between Edinburgh and central England. The contrast is least in winter and greatest in summer, with autumn and spring occupying intermediate positions. Figure 2.1b compares the two series for the winter season (December of the preceding year, January and February). The mean temperature for central England was 3.6°C while that for Edinburgh was 3.3°C, a difference of only 0.3°C (Table 2.1). There is consistency between the two records especially after 1851. The r value for winter temperature is 0.690. This result is significantly different from 0 at the P=0.001 level. However, it is the smallest correlation of the four seasons.

The small difference in winter temperature is found today. London's mean January temperature is 4.4°C and Edinburgh's mean January temperature is 4.0°C. This may be explained by the following. In winter, the surface temperature of the North Sea remains relatively high when compared with the ground surface temperatures over the adjacent coastal areas of northern Europe. Air masses passing over Scotland from the continent track over the North Sea and are warmed by the sea before reaching Edinburgh. In contrast, easterly winds passing over England from the continent, have a much shorter track over the sea before reaching Kent or East Anglia. Thus, these air masses retain the colder temperatures of the continent (Weston pers. comm. 1990). Also relevant is the sharp longitudinal trends in temperature gradient, induced by the warm water of the North Atlantic Drift on the west coasts of Britain.

Figure 2.1b, reveals that the variability of winter temperature over time. Periods of high variability occurred between the years 1780-1820, 1843-1850 and 1890-1896: and periods of less variability in the years 1820-1840 and 1850-1890. Even today, the fluctuation of winter mean temperature is much greater than in any other season of the year (Chandler et al. 1976).

The variability of winter temperature is greater than for other seasons of the year. This is illustrated by the standard deviation (SD), a measure of the variability. In central England, the winter standard deviation is 1.5 times greater than in spring; 1.6 times greater than in summer and 1.8 times greater than in autumn. In Edinburgh, the winter standard deviation is 1.4 times greater than in spring; 1.6 times greater than in summer and 1.6 times greater than in autumn. This greater winter variability is not just a feature of the past. Between 1921-1950, fifty-two weather stations around Britain were surveyed and the deviations in winter temperatures were found to be twice as great as those in summer (Chandler et al. 1976).

The main feature of the comparison of spring temperatures (of March, April and May) is that the temperatures in central England are 0.9°C warmer than Edinburgh. The mean temperature for central England was 8.1°C, while the average spring temperature for Edinburgh was 7.2°C. The lower temperatures in Edinburgh reflect the higher latitude which reduces solar radiation, the lag effect of the North Sea which is slow to warm and the cold easterly winds.

There is consistency between the two temperature sets for spring. The r value for the spring season of the two data sets is 0.751 - the strongest seasonal correlation. Again, this result is significant at the P=0.001 level. There are also interesting changes over time. At certain times, cold and warm periods alternate. Frequency varies and is highest in the years 1853-67 and 1867-96 and lowest in the years 1816-53. There was a continual decline in mean spring temperature in the years 1802-07.

Figure 2.1d is a graph of the English and Scottish temperatures for the summer season (June, July and August). The mean temperature for central England was 15.2°C. The average summer temperature for Edinburgh was 14.1°C. This temperature difference of 1.1°C is the greatest of the four seasons. The effects of latitude and reduced continentality are responsible for Scotland's lower temperature.

Figure 2.1d reveals considerable consistency between the two records. The r value is the second highest at 0.736 and is significant at the P=0.001 level. Cool summers occurred between 1809-16 and 1838-41. Prior to 1860, warm and cool summers alternated more slowly than after 1860.

Figure 2.1e displays mean autumn temperatures (for September, October and November) for Edinburgh and central

England. The mean autumn temperature for central England was 9.4°C and compared to 8.6°C in Edinburgh.

Again, there is good consistency between the records. The correlation coefficient is 0.705; this is significant at the P=0.001 level.

The stability of the mean temperature over time becomes apparent in Fig. 2.1e. The main fluctuations were the series of cooler autumns which occurred in the years 1812-17, 1836-45 and 1885-92. Other cold autumns occurred in 1799, 1829, 1853, 1855, 1860 and 1879.

Seasonal comparisons show a strong agreement between the English and Scottish records; the correlation coefficients range from 0.690 to 0.751, all of which are significantly different from 0 at the P=0.001 level. With the exception of winter, seasonal temperatures differ by almost a full 1°C, as do the annual average temperatures. In spring, the seasonal temperature differs by 0.9°C and in autumn by 0.8°C. In summer, the difference is greater than 1°C. Only in winter is the seasonal difference significantly less.

EXTRAPOLATING THE EDINBURGH RECORD BACK TO 1659

It is possible to use the agreement between the shorter Edinburgh record and the longer record for central England, to extend the Edinburgh record. The seasonal stability and the consistent difference of 0.8°C in mean annual temperature over a number of cycles of climatic warming and cooling, suggested any such extrapolation is justified. On this basis, Edinburgh's mean annual temperatures could be estimated for the years 1659-1763 by subtracting 0.8°C from Manley's values for central England, for the same period (Table 2.3)

The standard deviations, however, imply that for such an extrapolation, about one of the mean annual temperatures, between 1659 and 1763, is likely to be ± 1.4°C incorrect; and about five temperatures are likely to be ± 0.9°C wrong.

THE EDINBURGH RECORD BEFORE 1659

Reconstruction of temperatures earlier than 1659 is fraught with difficulty, beacuse no instrumental records exist in Great Britain. In such a case it is necessary to try an alternative approach. In fact, two approaches were attempted: the use of tree rings and meteorological descriptions.

TREE RINGS

It is commonly accepted that tree-rings contain a climatic signal, which can be distinguished from background noise such as tree species, age, food storage within a tree and soil nutrients (Bradley 1985). Tree-rings, like instrumental records, provide a climatic record with a minimum sampling interval of one year and a dating accuracy of one year. Tree-ring chronologies would, in principle, be useful in extending back the Scottish temperature record (as well as the Edinburgh precipitation record).

The calculated climatic signal of several European chronologies ranges from 10-38% (Schmidt 1977); 45% (Hughes

Table 2.3 Mean Annual Temperature for Edinburgh 1659-1763

Year	Temperature	Year	Temperature
1659	8.0	1701	7.9
1660	8.3	1702	8.5
1661	8.3	1703	8.3
1662	8.7	1704	8.3
1663	7.8	1705	7.9
1664	8.5	1706	9.0
1665	7.5	1707	8.6
1666	9.0	1708	8.9
1667	7.9	1709	7.9
1668	8.7	1710	8.7
1669	8.2	1711	8.6
1670	8.1	1712	8.3
1671	8.3	1713	7.8
1672	8.1	1714	8.6
1673	7.9	1715	8.6
1674	7.4	1716	7.6
1675	7.1	1717	8.2
1676	8.0	1718	8.5
1677	7.9	1719	8.7
1678	7.7	1720	8.3
1679	8.1	1721	8.1
1680	8.0	1722	8.5
1681	7.9	1723	9.0
1682	8.2	1724	8.5
1683	7.7	1725	7.9
1684	7.1	1726	8.5
1685	8.3	1727	9.1
1686	9.4	1728	8.7
1687	8.0	1729	8.5
1688	7.0	1730	9.3
1689	7.7	1731	9.0
1690	8.1	1732	8.9
1691	7.2	1733	9.6
1692	6.9	1734	9.0
1693	7.6	1735	8.8
1694	6.9	1736	9.5
1695	6.4	1737	9.1
1696	7.7	1738	9.0
1697	7.2	1739	8.4
1698	6.9	1740	6.0
1699	8.0	1741	8.4
1700	8.3	1742	7.6

1743	9.0
1744	8.0
1745	8.0
1746	7.8
1747	9.0
1748	8.0
1749	8.6
1750	8.9
1751	7.6
1752	8.4
1753	8.2
1754	8.0
1755	7.8
1756	8.0
1757	8.0
1758	8.2
1759	9.2
1760	9.0
1761	9.2
1762	8.8
1763	8.1

et al. 1978); 34-64% (Hughes et al., 1978) and 22-64% (Pilcher et al. 1980) of the chronology variance. More recently, Pilcher et al. (1980) have published eight oak chronologies from England and Scotland, whose percent variance attributable to climate has ranged from 33-72%. This figure shows (1) a similar range to those already presented in Europe and (2) a good climatic signal in the oak chronologies.

In light of the above, it was necessary to find tree-ring indices which extend back beyond 1659. Baillie (1973) has established an Irish chronology dating back to 1001 A.D. Pilcher (1973) has outlined objectives to construct a long Irish chronology extending back to at least 4000 B.C. for dendroclimatic studies. Unfortunately, no lengthy chronologies have been established for Scotland or England. Seven of the eight chronologies for England and Scotland by Pilcher et al. (1980), only date from the eighteenth or even nineteenth centuries. However, these chronologies might be extended if it could be demonstrated that: (1) there were considerable overlap between the English and Irish chronologies and (2) there were a good climatic signal of temperature and precipitation in the English trees.

As a first step towards the possible extension of the English record, it was necessary to determine what climatic signal, if any, existed in these trees. In order to achieve this, a critical comparison of oak tree-ring indices and historical instrumental records was undertaken.

Good climatic records are thought to be represented by oak tree-ring records at Blickling, Bath and Oxford and as a result, these can be compared to instrumental records in central England.

The three main oak chronologies referred to above are, Blickling (1717-1978), Bath (1754-1978) and Oxford I and II (1781-1978). There is overlap between these chronologies and existing instrumental climatic records. These include a temperature record from central England for the years 1659-1973 (Manley 1974); a precipitation record for Kew for 1697-1977 (Lamb 1977) and a precipitation record from Oxford for 1800-1829 (Craddock et al. 1977).

Method

The overall approach used here, was to compare both the seasonal and annual weather against tree-ring characteristics. First, each of the indices for the three oak tree-ring sites was correlated with temperature data for the English Midlands in winter, spring, summer, autumn and the year as a whole. Time lags of one, two, three, four and five years were introduced, with the tree-ring data lagging the temperature record. Second, the oak chronologies were compared to the seasonal and yearly rainfall records at Kew. Again, lags of one to five years were introduced. As a final step, correlation analysis was employed to compare the Oxford chronology with the precipitation record at Oxford. Here too, lags of one to five years were once again introduced.

Results

Table 2.4 presents the results of correlation analysis

Table 2.4

Comparison of the Oak Tree Ring Widths at Blickling, Bath, and Oxford with the Central England Instrumental Temperature Record of Manley (1974)

Correlation Coefficients

Site	Winter	Spring	Summer	Autumn	Annual
Blick.	0.055	0.147	0.122	0.096	0.166
Bath	-0.042	0.012	-0.052	0.137	0.040
Oxford	0.140	-0.001	-0.087	0.039	0.070

n=100 Significant r values at p=.05= .1946

Table 2.5

Comparison of the Lagged Chronologies with the Central England Instrumental Temperature record of Manley (1974)

Correlation Coefficients

Site	Season	Lags of Years -1	-2	-3	-4	-5
Blick.	Winter	0.078	0.159	0.049	-0.070	-0.110
	Spring	0.083	0.054	0.157	0.040	-0.003
	Summer	-0.039	-0.030	0.019	-0.084	-0.077
	Autumn	0.028	0.188	0.238	0.201	0.017
	Annual	0.064	0.122	0.156	0.016	-0.061
Bath	Winter	0.151	0.275	0.139	0.057	0.032
	Spring	0.121	0.044	0.134	0.210	0.139
	Summer	0.156	0.098	0.050	0.087	0.046
	Autumn	0.096	0.251	0.253	0.191	0.025
	Annual	0.144	0.228	0.257	0.189	0.098
Oxford	Winter	0.208	0.153	0.127	0.014	0.098
	Spring	0.187	0.189	0.071	0.152	0.164
	Summer	0.094	0.103	0.133	0.144	0.071
	Autumn	0.058	0.214	0.089	0.105	0.010
	Annual	0.201	0.249	0.172	0.208	0.127

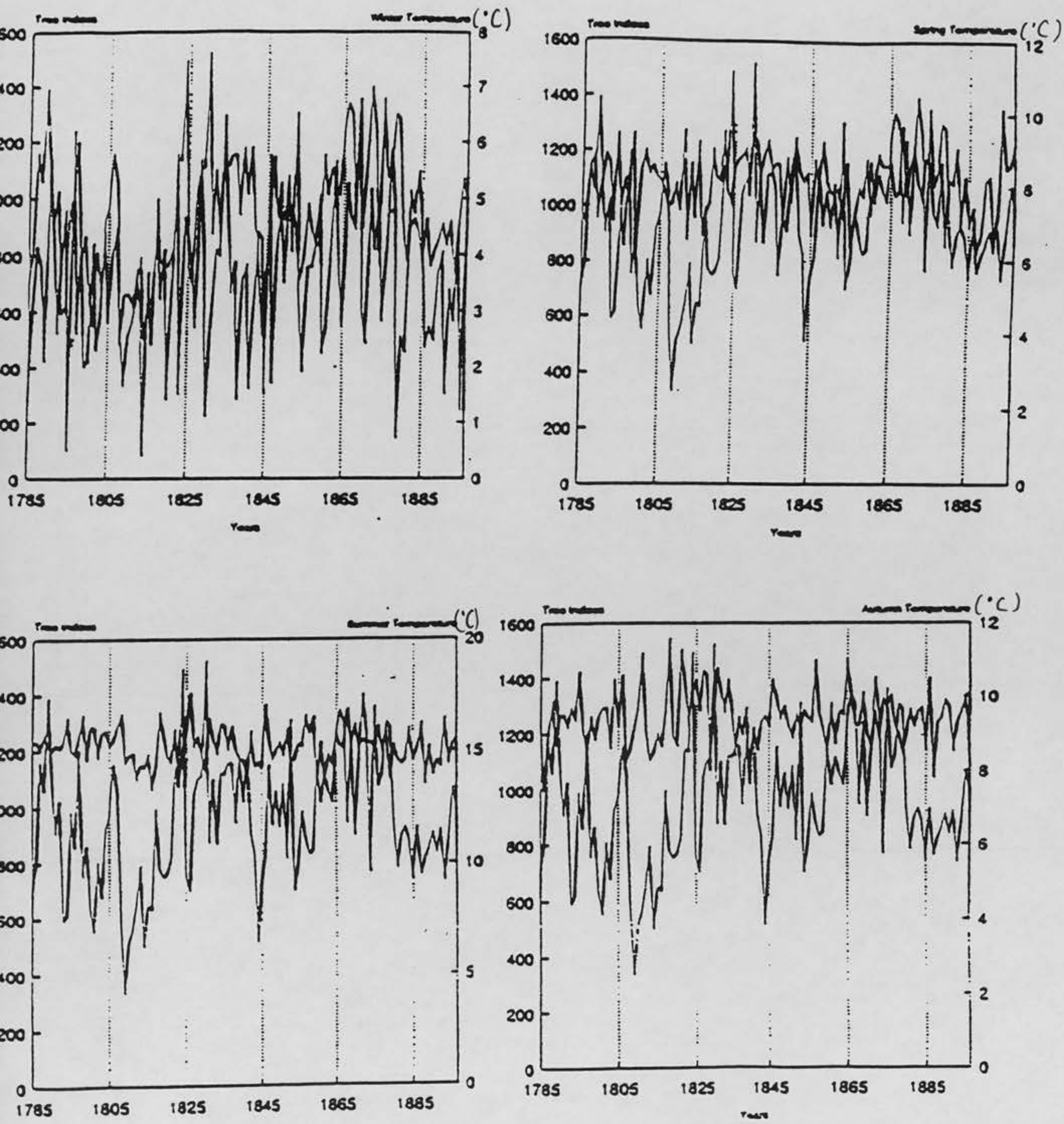
n=100 Significant r values at p=.05=.1946

for each of the tree-ring indices at each site, with seasonal and annual temperatures. Figure 2.2 compares the tree-ring indices at Oxford with temperatures in the Midlands. The Oxford record was chosen because it has the highest percent variance attributable to climate.

From Table 2.4 and Figure 2.2, it is apparent that there is only a poor correlation between the oak tree-ring record and the seasonal and annual temperatures in central England. Indeed, the highest correlation coefficient, or r value, is 0.166. This result is not significantly different from 0 at the P=0.05 level. The square of the correlation coefficient, or r^2, is referred to as the coefficient of determination and indicates the proportion of the total variation explained. In this case, therefore, temperature explains only 2.76% of the variation. The expression $1-r^2$ gives the proportion of variation left unexplained, often written as a percentage (Clarke et al. 1986). In this example 97.24% of the variation remains unexplained.

Table 2.5 presents the results of correlation analysis of the ring-width data with the seasonal and annual temperature data, using time lags of one to five years. Once again, the correlation between the two data sets is very poor. The highest r value remains low at 0.275, but this is over 10% higher than that of the highest correlation, without any lags. In general, the r values for the lagged data appear to be stronger than that of the non-lagged data. Results significantly different from 0 occur for one to five year lags. However, these results

2.2 Tree-Ring Indices at Oxford With Temperatures in Central England



still leave 92.44% of the variation unaccounted for.

Table 2.6 shows the results of correlation analysis for the record of tree-ring width at all three sites, with the precipitation at Kew. Figure 2.3 shows the relationship between tree-ring indices for the oak chronology at Bath with precipitation at Kew. One of the notable features of the table is the extremely poor correlation between the tree-ring record at Blickling and seasonal and annual precipitation at Kew (the r values range from 0.001-0.067). The tree-ring records at Bath and Oxford, however, show a greater correlation with the precipitation record. For both sites, the highest r value is for summer precipitation: Bath 0.349 and Oxford 0.317. These values are significantly different from 0 at the P=0.01 level. The r values for summer and annual precipitation at Bath and Oxford are significantly different from 0; the r value for winter precipitation at Oxford is also significantly different. Despite the fact that the correlations are significantly different from 0, 87.82% of the variation remains unexplained.

Table 2.7 presents the results of correlation analysis between the tree-ring data and the precipitation data, with time lags of one to five years. The correlation between the two data sets is very poor; the highest r value is only 0.288; this is significant at the P=0.01 level. The r values are significant one, two and four years later. However, 92.32% of the variation remains unexplained.

Table 2.8 gives the results of correlation analysis for the tree-ring record at Oxford and precipitation data

Table 2.6

Comparison of the Oak Tree Ring Widths at Blickling, Bath, and Oxford with the Kew Precipitation Record of Lamb (1977)

	Correlation Coefficient				
Site	Winter	Spring	Summer	Autumn	Annual
Blick.	0.001	0.080	0.067	0.008	0.003
Bath	0.113	0.109	0.349	0.013	0.287
Oxford	0.242	0.101	0.317	0.151	0.335

n=90 Significant r values at p=.05=.2050

Table 2.7

Comparison of the Lagged Chronologies with the Kew Instrumental Precipitation Record of Lamb (1977)

		Correlation Coefficient				
Site	Season	Lags of Years				
		-1	-2	-3	-4	-5
Blick.	Winter	0.033	-0.079	-0.051	-0.024	0.038
	Spring	-0.122	-0.243	0.006	0.153	0.277
	Summer	0.194	0.056	0.100	0.026	0.040
	Autumn	0.045	0.017	0.147	0.061	-0.097
	Annual	0.056	-0.054	0.074	0.058	0.020
Bath	Winter	0.109	0.185	0.074	-0.044	0.111
	Spring	0.017	0.122	0.101	0.040	0.135
	Summer	0.049	0.136	-0.057	-0.141	-0.111
	Autumn	-0.012	-0.156	-0.021	-0.156	-0.085
	Annual	0.043	0.081	0.081	-0.148	-0.052
Oxford	Winter	0.023	0.095	0.029	-0.022	0.013
	Spring	-0.084	0.003	0.018	0.061	0.164
	Summer	0.214	-0.039	-0.112	-0.150	-0.032
	Autumn	0.181	-0.147	0.113	0.067	0.023
	Annual	0.288	-0.101	0.045	-0.003	0.012

n=80 Significant r values at p=.05=.2172

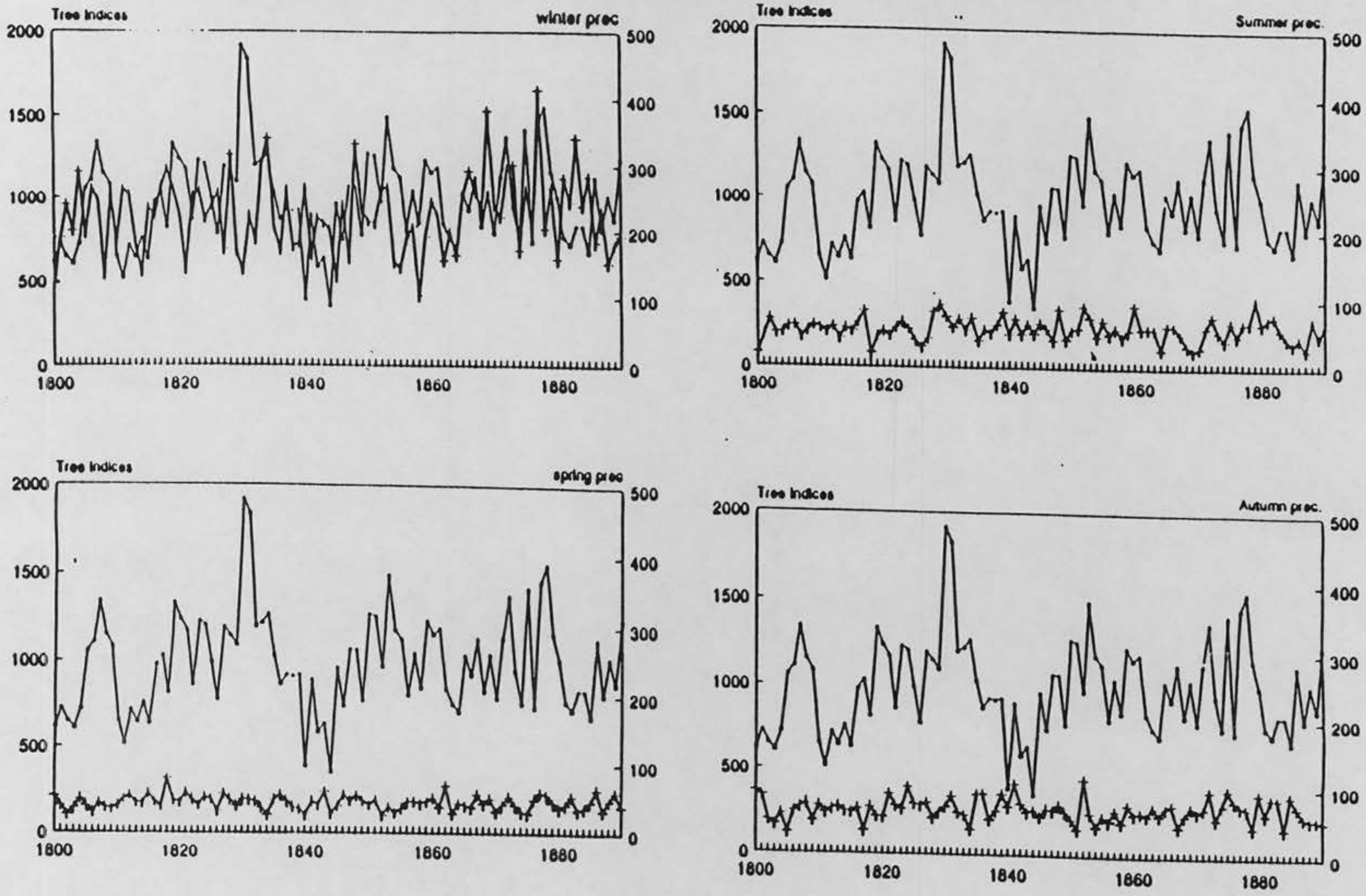


Fig. 2.3 Tree-Ring Indices at Bath With Precipitation at Kew

Table 2.8

Comparison of the Oak Tree Ring Width Chronology at Oxford with the Oxford Precipitation Record of Craddock et al., (1977)

Correlation Coefficients

Site	Annual	Lags of Years				
		-1	-2	-3	-4	-5
Oxford	-0.044	?	-0.356	-0.142	-0.387	0.074

n=30 Significant r values at p=.05=.3494

recorded instrumentally, for the same period. Also shown are the correlations with lags of one to five years. The non-lagged r value of - 0.044, indicates that there is virtually no correlation between the indices and the precipitation record. There were stronger correlations when lags of two and four years were introduced; indeed, these r values were found to be significant at the P=0.05 level. Despite their significance, 85.02% of the variance remains unexplained.

Discussion

A surprising conclusion is that there is a poor correlation between the oak tree-ring indices and recorded temperatures. This lack of agreement may be explained in three ways. (1) The recorded temperature data may not relate closely to the temperatures experienced by the trees. This, however, seems unlikely as it has been demonstrated that anomalous large-scale weather patterns (as well as site-specific climate) can be detected in tree growth over wide areas (Fritts et al. 1971; Hughes et al. 1978). (2) The English data contains both seasonal and annual mean temperatures which are necessarily averaged over several months. Tree-ring indices, however, are often related to the temperatures of individual months. Despite this, higher correlations were expected, especially in the growing season. (3) The oak samples were not taken close to the oak climatic limit. In such a case, temperature may not impose growth limitations and thus, ring-width variations would not be expected to contain a strong temperature signal.

In light of the above, the poor agreement is best explained by the lack of temperature stress and hence the lack of a temperature signal in the oaks. The implication, of this is that the English oak chronologies contain a poor temperature signal and therefore, it would be erroneous to utilize these chronologies in any reconstructions of past temperature.

The weak relationship between precipitation and ring-width can be explained in a similar way. Perhaps, the oaks are not at their climatic limit and hence, are not stressed by any one climatic parameter. It has been shown that the oak indices at Bath and Oxford relate most closely with summer precipitation ($r = 0.349$ and 0.317 respectively) and annual precipitation ($r = 0.287$ and 0.335 respectively). This suggests the trees are somewhat drought sensitive; a conclusion which agrees with the conclusions of Pilcher et al. (1976) who found drought sensitive trees in the north of Ireland. Although the correlations are significantly different from 0, 87.81% of the variation remains unexplained. The poor correlations and lack of explained variation imply that it would be incorrect to extract any precipitation signal from the tree-ring record.

Although there is a weak correlation between the three chronologies and precipitation; there is virtually no correlation between the tree-ring record at Oxford and precipitation recorded at the same place. The poor correlation is not simply the result of averaging precipitation values. The r values, comparing Oxford and Bath with annual precipitation at Kew, were significant at

0.335 and 0.287 respectively. The insignificant correlation for the oak ring-widths and precipitation at Oxford, seems to provide support for those who suggest that a climatic signal cannot be extracted from one site alone. Any precipitation patterns may be better detected in tree growth pattern over wide areas.

Two major implications arise from the analysis of tree-ring records and climate.

First, none of the three tree-ring width series should be utilized in reconstructions of past seasonal or annual temperature and precipitation. This is because: (1) the ring-width series all show poor correlations with records of recorded instrumental temperature and precipitation and (2) temperature and precipitation, at best, only account for 2.76-12.18% of the total variation in ring-width, for the same year. Any climatic reconstructions would be extracting more information than the value of the data justifies. Pilcher et al. (1980) suggest the percentage variance attributable to climate (i.e. temperature and precipitation) for Blickling, Bath and Oxford are 40%, 43% and 50%, respectively. Probably, these estimates are much too high.

Second, multi-site reconstructions appear to be more reliable in palaeoclimatic reconstructions, than do individual-site reconstructions. The correlations between the Bath and Oxford tree-ring chronologies and the Kew precipitation record are much stronger than is the correlation for the Oxford tree-ring chronology and the Oxford precipitation record.

Because the English chronologies contain a poor climatic signal, no attempt was made to see if the English and Irish indices were well correlated. An extension of the instrumental temperature record was only justified if it could be demonstrated that there were a good correlation between the English chronologies and the established weather records. In view of this, an alternative method for establishing past Scottish temperature was sought.

METEOROOGICAL DESCRIPTION

Lamb (1977) made use of meteorological descriptions, along with evidence from wine harvests in Luxembourg and Baden and from ice on the Baltic, to construct indices of winter severity and summer wetness for the period 800-1950 A.D in England. Fifty-year averages of these indices were then derived, using regression equations based on comparison with records for 1680-1740 (Manley 1974). These resulting temperatures are in fact, the only available temperature estimates.

Despite the obvious uncertainties associated with such records, they are almost certainly reliable indicators of the most severe decades in medieval central England. There are further difficulties in using decade indices to derive long-term temperature trends. Furthermore, the preferred temperature values prior to 1400 AD are Lamb's own opinion. This opinion is based on an analysis of various proxy indicators.

The changes established for England are accepted by Lamb as being common to Scotland, and this study supports Lamb's assertion. It would seem reasonable to assume that the covariation, established for the years 1764-1896, also occurred at earlier periods.

In light of the above, 0.8^{0}C was subtracted from each of Lamb's high summer (July and August), winter (the preceding December, January and February) and mean values. This last figure is derived from the average of the winter and summer values (Table 2.9). It is useful to go further and obtain additional seasonal estimates for spring and autumn. Two approaches were tried in order to achieve this. The first involved interpolation between the adjusted high summer and winter temperatures on a sine curve. The maximum temperature occurs in July and the minimum temperature in January. These two months were plotted at the maximum and minimum points on the sine curve. The values for the remaining months were then calculated using 30^{0} intermediate points (Fig. 2.4). This procedure employed use of the multiplier fraction (Sin Dj+1)/2 (Table 2.10). Sine Dj means the sine of the degree of a particular month. Mean monthly temperatures were calculated using the formula:

$$T = L\ (\mathrm{Sin}\ Dj+1)/2$$

where T=Temperature
L=Low Temperature

In order to determine whether the sine function is representative of monthly mean temperature, the following test was undertaken. Using Mossman's (1896) data for the period 1764-1896, actual monthly mean values were

Table 2.9

Central England's and Edinburgh's Mean Annual, Winrer, and High Summer Temperatures.

Period(AD)	C.Eng.($\bar{x}$)	Edin.($\bar{x}$)	C.Eng.(W)	Edin.(W)	C.Eng.(S)	Edin.(S)
800-1000	9.2	8.4	3.5	2.7	15.9	15.1
1000-1100	9.4	8.6	3.7	2.9	16.2	15.6
1100-1150	9.6	8.8	3.5	2.7	16.5	15.7
1150-1200	10.2	9.4	4.2	3.4	16.7	15.9
1200-1250	10.1	9.3	4.1	3.3	16.7	15.9
1250-1300	10.2	9.4	4.2	3.4	16.7	15.9
1300-1350	9.8	9.0	3.8	3.0	16.2	15.4
1350-1400	9.5	8.7	3.8	3.0	15.9	15.1
1400-1450	9.1	8.3	3.4	2.6	15.8	15.0
1450-1500	9.0	8.2	3.5	2.7	15.6	14.8
1500-1550	9.3	8.5	3.8	3.0	15.9	15.1
1550-1600	8.8	8.0	3.2	2.4	15.3	14.5
1600-1650	8.8	8.0	3.2	3.4	15.4	14.6
1650-1700	8.7	7.9	3.1	2.3	15.3	14.5
1700-1750	9.2	8.4	3.7	2.9	15.9	15.1
1750-1800	9.1	8.3	3.4	2.6	15.9	15.1
1800-1850	9.1	8.3	3.5	2.7	15.6	14.8
1850-1900	9.1	8.3	3.8	3.0	15.7	14.9
1900-1950	9.4	8.6	4.2	3.4	15.8	15.0

Derived from Lamb(1977).

Calculation of the Multiplier Fraction

Table 2.10

Month	Dj	SinDj	Fraction
1	270	-1.000	0.000
2	300	-0.866	0.067
3	330	-0.500	0.250
4	360	0.000	0.500
5	30	0.500	0.750
6	60	0.866	0.933
7	90	1.000	1.000
8	120	0.866	0.933
9	150	0.500	0.750
10	180	0.000	0.500
11	210	-0.500	0.250
12	240	-0.866	0.067

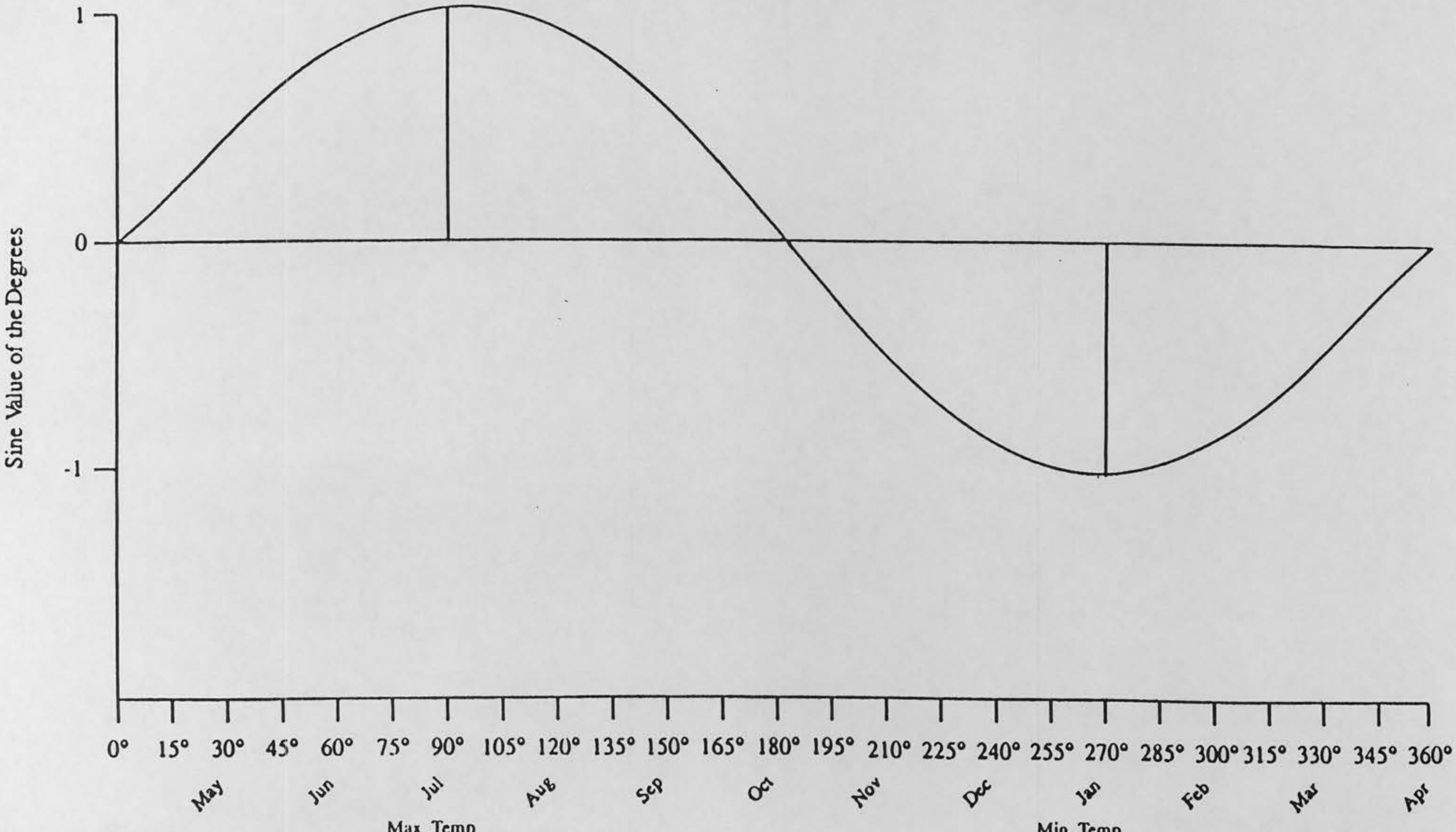


Fig. 2.4 Sine Curve and Months of the Year

compared with the sine values. Figure 2.5 shows the comparison. It was found that the sine curve did not accurately fit the monthly values and under-estimated January's temperature, but over-estimated the mean values for the months March to August. The spring values are over-estimated to the greatest extent, because south-eastern Scotland is slow to 'warm up' in the spring. The best fit agreement is in February and October. The sine curve fitted the August and September well, but over-estimated the value for November. In conclusion, the sine curve was found to be an inadequate means of interpolating monthly temperatures.

The second approach was to rely on the actual temperature data. Table 2.11 shows the procedure involved. Column 3 contains the mean monthly temperatures for the twelve months, for the period 1764-1896. Column 4 shows the re-scaled temperature data which were found as follows. The average winter temperature for the 132 years was calculated from the three winter months (December-February) and yielded a value of 2.9^{0}C. Similarly, the mean summer temperature was calculated from the July and August temperatures, as being a figure of 14.5^{0}C. The average low temperature for each month was subtracted to produce the re-scaled data. Column 5 contains the empirical fraction, which is the equivalent of the sine fraction. The empirical fraction was calculated by dividing the values in Column 4, by the mean temperature range for the whole period (i.e. 14.5 - 2.9 = 11.6).

The mean monthly temperatures may then be calculated

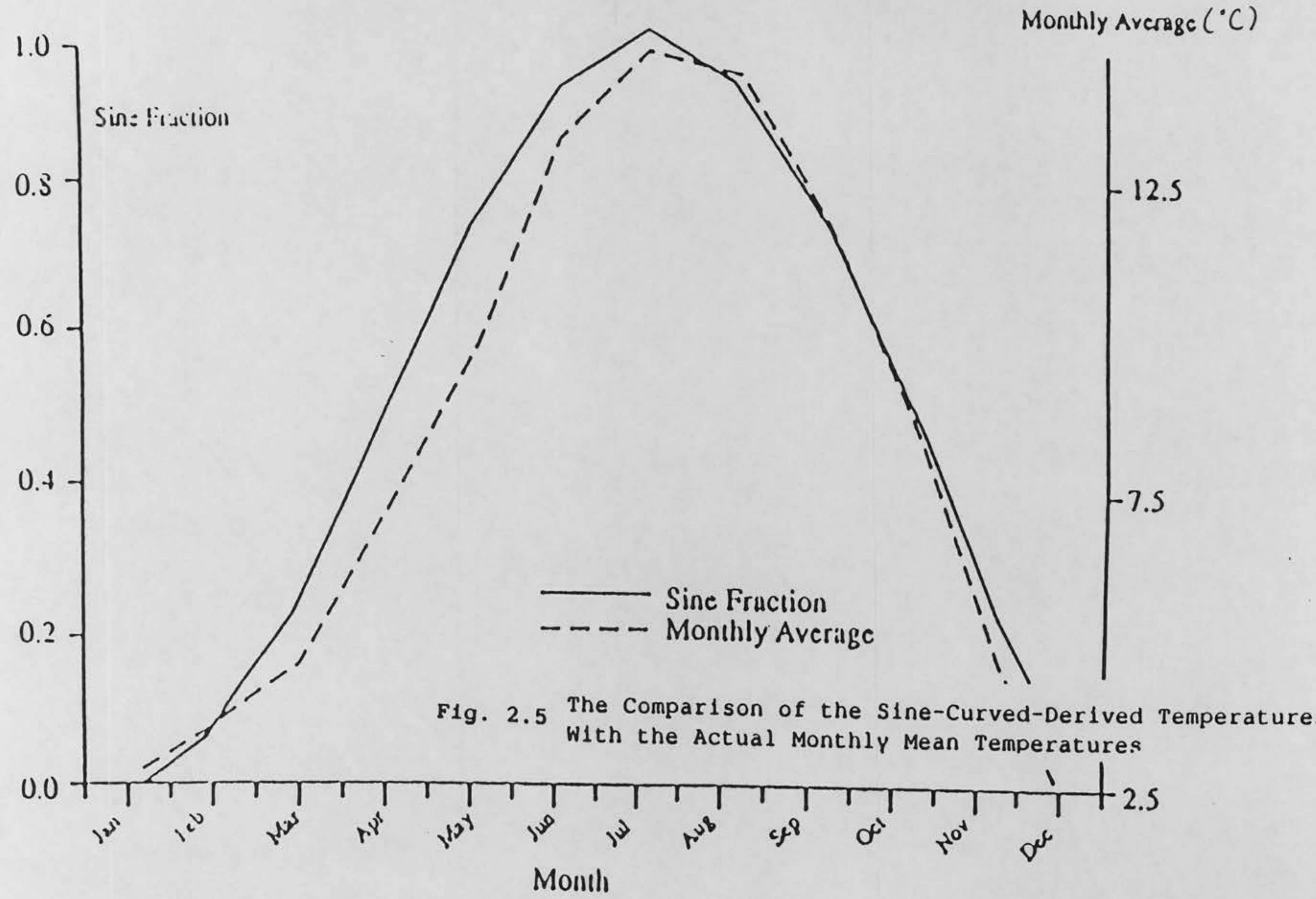


Fig. 2.5 The Comparison of the Sine-Curved-Derived Temperatures With the Actual Monthly Mean Temperatures

Table 2.11

Calculation of the Empirical Fraction

Month	Sine fraction	Monthly temp.	Month-low	Empir.fraction
1	0.000	2.7	-0.2	-0.017
2	0.067	3.5	0.6	0.052
3	0.250	4.6	1.7	0.147
4	0.500	7.1	4.2	0.362
5	0.750	9.9	7.0	0.603
6	0.933	13.2	10.3	0.888
7	1.000	14.7	11.8	1.017
8	0.933	14.3	11.4	0.983
9	0.750	12.0	9.1	0.784
10	0.500	8.4	5.5	0.474
11	0.250	4.9	2.0	0.172
12	0.067	2.5	-0.4	-0.034

for the required period utilizing the formula:

$$T = L + (\text{range}) \times \text{empirical fraction}$$

Figure 2.6 shows a comparison of the sine fraction with the empirical fraction. It shows that using the empirical fraction avoids the seasonal anomalies encountered with using the sine fraction. The resultant temperatures using the empirical fraction can be viewed in Table 2.12.

This temperature record shows the same trends as Lamb (1977): notably the Medieval Warm Epoch 1150-1300 AD, when mean annual temperature was 0.7°C warmer than today; the climatic worsening of 1300-1500 AD, when average annual temperatures fell by 0.5°C; the temporary return to warmer climate, with a rise in temperature of 0.3°C in the years 1500-1550 AD; the Little Ice Age of 1550-1700 AD when mean annual temperature was 0.7°C cooler than today and a general change toward higher temperature from 1700 AD onwards.

This new record is more representative of Scotland's temperature than the central England record because: (1) it has been adjusted to be representative of Edinburgh and (2) it has monthly values which are calibrated with an instrumental record in Edinburgh.

PRECIPITATION

Today, there exists only one comprehensive rainfall record for all of Scotland, that of Mossman (1896). It covers Edinburgh for the years 1770-1896. Because a much

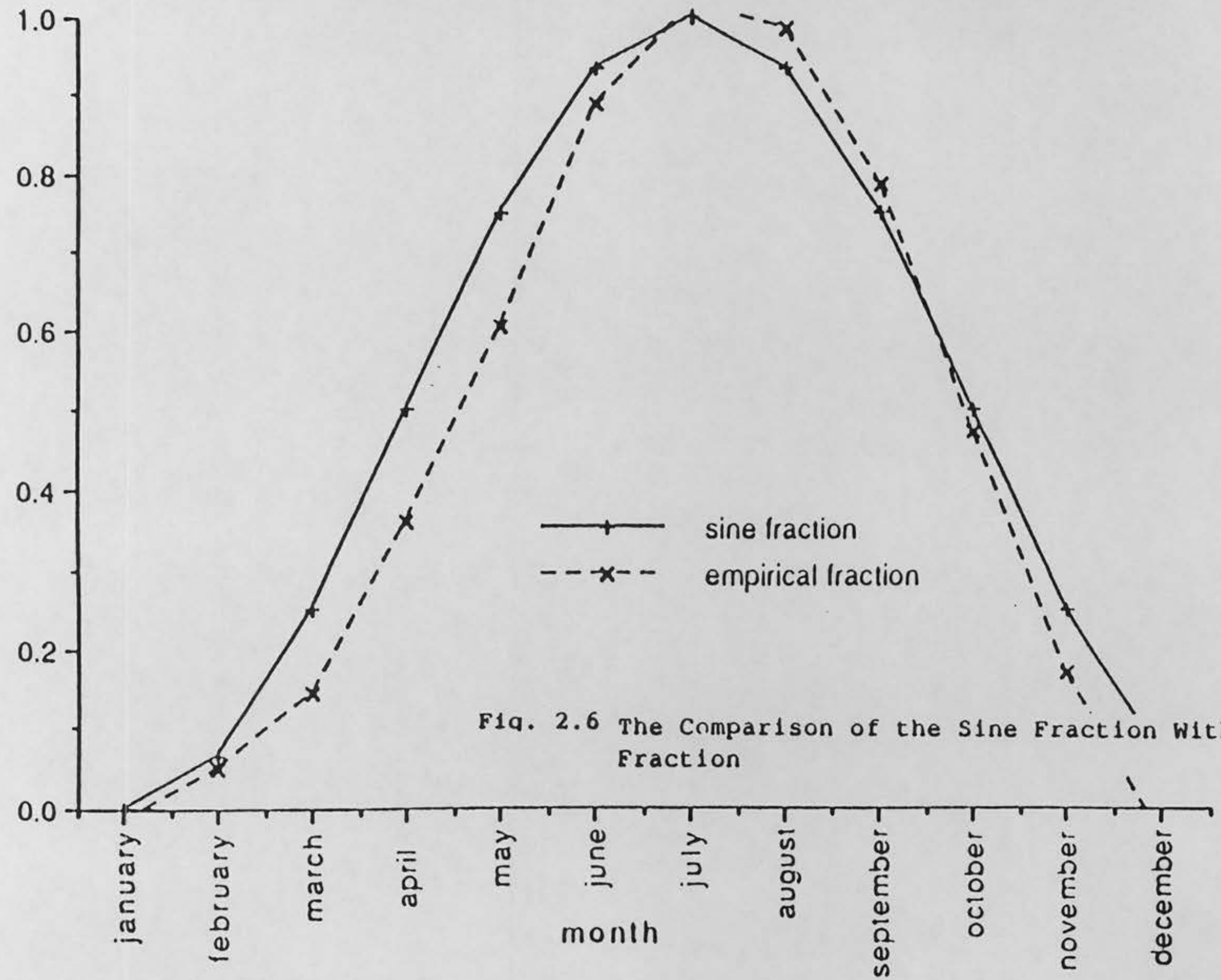


Fig. 2.6 The Comparison of the Sine Fraction With the Empirical Fraction

Edinburgh's Mean Monthly Temperature for 800-1900AD

Table 2.12

Month	Temperature For the Period 800-1000 AD	For 1000-1100 AD
J	2.5	2.7
F	3.3	3.6
M	4.5	4.8
A	7.2	7.5
M	10.2	10.6
J	13.7	14.2
J	15.3	15.9
A	14.9	15.4
S	12.4	12.9
O	8.6	8.9
N	4.8	5.1
D	2.3	2.5

	For 1100-1150 AD	For 1150-1200 AD
J	2.5	3.2
F	3.4	4.1
M	4.6	5.2
A	7.4	7.9
M	10.5	10.9
J	14.2	14.5
J	15.9	16.1
A	15.5	15.7
S	12.9	13.2
O	8.9	9.3
N	5.2	5.6
D	2.3	3.0

	For 1200-1250 AD	For 1250-1300 AD
J	3.1	3.2
F	4.0	4.1
M	5.2	5.2
A	7.9	7.9
M	10.9	10.9
J	14.5	14.5
J	16.1	16.1
A	15.7	15.7
S	13.2	13.2
O	9.3	9.3
N	5.5	5.6
D	2.9	3.0

For 1300-1350 AD

J	2.8
F	3.6
M	4.8
A	7.5
M	10.5
J	14.0
J	15.6
A	15.2
S	12.7
O	8.9
N	5.1
D	2.6

For 1350-1400 AD

2.8
3.6
4.8
7.4
10.3
13.7
15.3
14.9
12.5
8.7
5.1
2.6

For 1400-1450 AD

J	2.4
F	3.6
M	4.4
A	7.1
M	10.5
J	14.0
J	15.2
A	14.8
S	12.3
O	8.5
N	4.7
D	2.1

For 1450-1500 AD

2.5
3.3
4.5
7.1
10.0
13.4
15.0
14.6
12.2
8.4
4.8
2.3

For 1500-1550 AD

J	2.8
F	3.6
M	4.8
A	7.4
M	10.3
J	13.7
J	15.3
A	14.9
S	12.5
O	8.7
N	5.1
D	2.6

For 1550-1600 AD

2.2
3.0
4.2
6.8
9.7
13.1
14.7
14.3
11.9
8.1
4.5
2.0

	For 1600-1650 AD	For 1650-1700 AD
J	2.2	2.1
F	3.0	2.9
M	4.2	4.1
A	6.8	6.7
M	9.8	9.7
J	13.2	13.2
J	14.8	14.8
A	14.4	14.3
S	12.0	11.9
O	8.2	8.1
N	4.5	4.4
D	2.0	1.9

	For 1700-1750 AD	For 1750-1800 AD
J	2.7	2.4
F	3.5	3.3
M	4.7	4.4
A	7.3	7.1
M	10.3	10.1
J	13.7	13.7
J	15.3	15.3
A	14.9	14.9
S	12.5	12.4
O	8.7	8.5
N	5.0	4.7
D	2.5	2.2

	For 1800-1850 AD	For 1850-1900 AD
J	2.5	2.8
F	3.3	3.6
M	4.5	4.8
A	7.1	7.3
M	10.0	10.2
J	13.4	13.6
J	15.0	15.1
A	14.6	14.7
S	12.2	12.3
O	8.4	8.6
N	4.8	2.1
D	2.3	2.6

longer rainfall record is needed in this study, a critical comparison of the Edinburgh record with the Pode Hole series of Craddock and Wales-Smith (1977) was undertaken, for the years 1770-1896. This procedure was done in order to determine if an extension of the Edinburgh record were possible. Pode Hole was chosen because it is located in eastern England; it is thought that this site is more likely to be representative of eastern Edinburgh than any of the other sites with existing weather records (Table 2.13).

The r value for Edinburgh and Pode Hole is low at 0.372. Although this result is significantly different from 0 at the p=0.05 level (.1946 for n=100), only 13.8% of the variation is explained. This lack of consistency between the two series may be explained by the fact that Pode Hole is an inland site with a more continental climate; whereas, Edinburgh is a coastal site, with a more maritime climate.

Lamb (pers. comm. 1989) expects very low r values for precipitation, because different sites have different factors, such as proximity to the sea, altitude, relief of the land and exposure to wind. Precipitation is highly regional in Britain. For example, in Scotland, the higher hills of the west and north receive heavy rainfall with annual precipitation often exceeding 1600 mm. Much of eastern and northern Scotland is relatively dry (The Meteorological Office 1989).

Reconstruction of Scottish precipitation earlier than 1770 AD is extremely difficult, because no instrumental

Table 2.13 Existing Historical Weather Records for Britain

Type of Record	Dates	Source
Manchester's prec.	1765-1972	(Manley 1972)
Scot. snowstorms	1782-1886	(Pearson 1973)
Scot. winter	1739-1740	(Pearson 1973)
Scot. weather	1659-1660	(Schove 1973)
Central Eng. temp.	1657-1973	(Manley 1974)
Seas. charactistics	1781-1784	(Kington 1974)
Oxford rainfall	since 1815	(Smith 1974)
England's prec.	since 1725	(Craddock 1976)
West Fife winter weather	18th century	(Kemp 1976)
Scot. snowstorms	1729-1830	(Pearson 1976)
Norwich rainfall	1836-1976	(Craddock 1977)
Oxford rainfall	1767-1814	(Craddock et al 1977)
English Midland rainfall	1726-1975	(Craddock et al 1977);
Central Eng. high summer wetness/dryness index	800-1950	(Lamb 1977)
Central Eng. winter mildness/severity index	800-1950	(Lamb 1977)
Potential moisture deficit: south-east Scotland	200 years	(Ledger 1977)
Norfolk weather	17th century	(Norgate 1977)
Kew potential	1698-1976	(Wales-Smith 1977)
Dry years south-east England	since 1698	(Wigley et al., 1977)
July to October	1588	(Douglas 1978)
Daily weather maps	1780s	(Kington 1978)
Variation in snowfall in east-central Scotland	1708-1975	(Manley 1978)

Scot. snowstorms	1831-1861	(Pearson 1978)
East Anglia climate	1250-1350	(Hallam 1979)
Climatic reconstruction	15th century	(Pilcher et al., 1979)
London summer and winter temperatures	1763-1980	(Finch 1980)
Cirencester homogoneous record	1844-1977	(Jones 1980)
Moor House temperature	1932-1978	(Manley 1980)
Central England temp. variability	1660-1977	(Schonwiese 1980)
Kew rainfall	1697-1976	(Wales-Smith 1980)
Central England and Netherlands temp.	1735-1981	(Hatch 1981-1982)
Extremes in Durham	1847-1981	(Harris 1982)
Britain's highest temp. on record		(Webb 1983)
Extremely cold periods of days at Oxford	Since 1881	(Webb 1983)
Homogeneity of central England temperature	Since 1659	(Probert-Jones 1984)
Changes in seasonal variation in the U.K.	1861-1980	(Smith 1984)
Revised homogeneous England and Wales prec. record		(Wigley et al., 1984)
Variations in Durham rainfall and temperature record	1847-1981	(Harris 1985)
Exeter temperatures	1840-1984	(Hay 1985)
Exeter temperatures	1782-1839 1985-1988	(Hay 1988)
Analysis of central England temperatures		(Matyasovszky 1989)
U.K. Maximum and minimum temperatures	1920-1989	(Tout 1990)
Analysis of area-average		(Gregory et

et al., data in Britain		al., 1991)
Birmingham temperatures	late 18th century	(Giles 1991)

records exist. In such a case, it is necessary to use various proxy records. Lamb (1977) made use of meteorological descriptions, along with evidence from wine harvests in Luxembourg and Baden and from ice on the Baltic to construct indices for summer wetness for the period 800-1950 AD (Fig. 2.7). Furthermore, Lamb (1977) established rainfalls as percentages of 1916-50 averages for England and Wales (Fig. 2.8). (This graph is particularly useful because it clearly shows the relative dryness of the years, 1150-1250 AD, compared to the relative wetness of later periods). Rainfalls from 1740 are based on averages taken from Nicholas and Glasspoole (1931) and Meteorological Office records. Rainfalls before 1740 are averages derived from decade values of the summer wetness/ dryness index and from the adjusted average values of mean annual and winter temperature, using regression equations.

The use of these proxy indicators to estimate precipitation in Scotland is thought to be a valid technique. This is because areas in England and Wales can be compared to approximately comparable areas in Scotland. For example, the English Lake District and the Welsh Mountains have similar precipitation patterns to the Scottish Highlands.

CONCLUSIONS

In conclusion, the climatic record for the current work includes the reconstruction of past Scottish temperature and past Scottish precipitation. This reconstruction is based on the following:

(1) The use of Manley's record and the mean annual

Fig. 2.7 Summer Wetness/Dryness Index

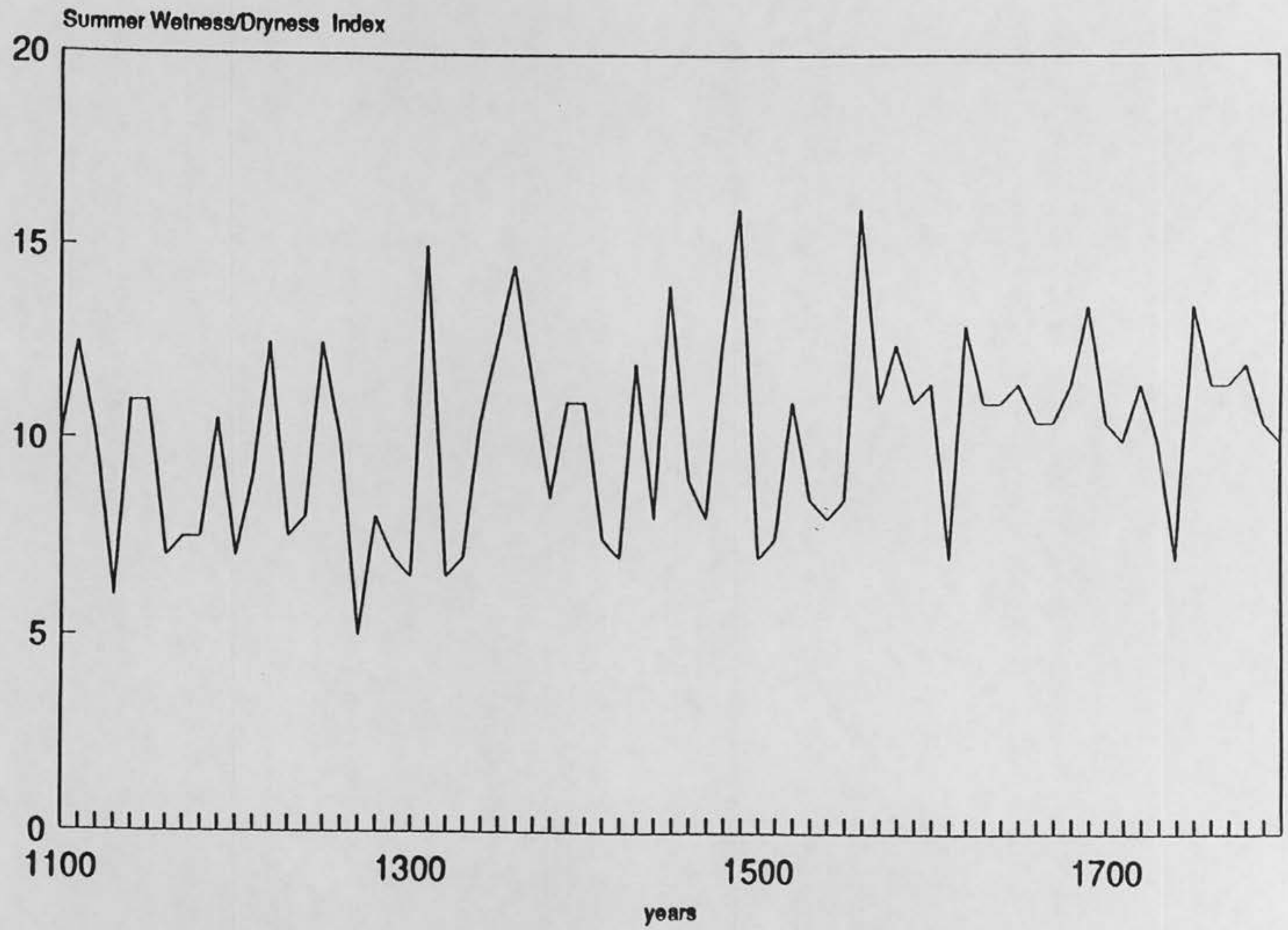
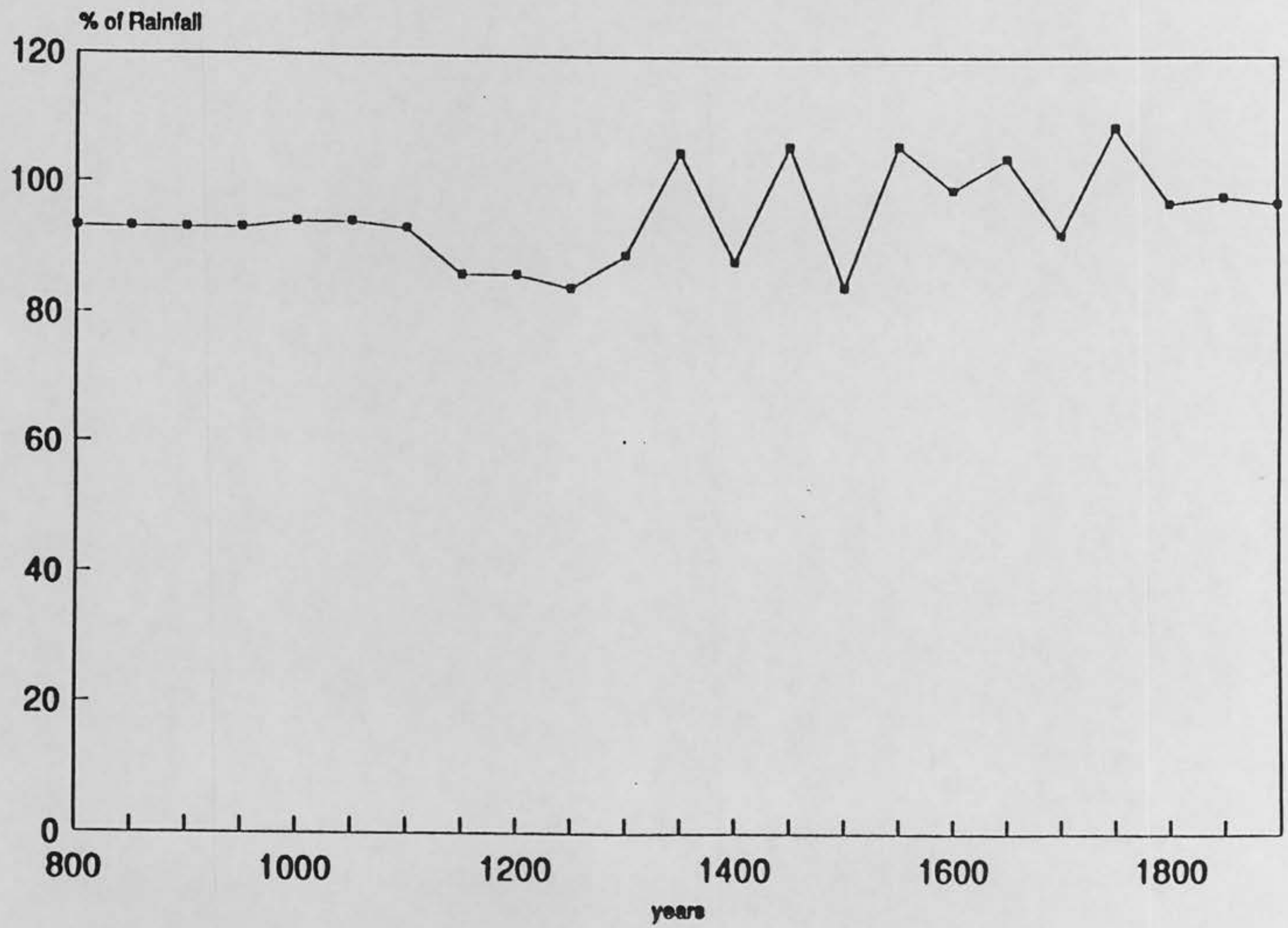


Fig. 2.8 High Summer (JA) Rainfalls(% of 1916-50 Averages) in England and Wales



difference in temperature between the Central England and Edinburgh data (i.e. 0.8°C), to extend the Edinburgh record back to 1659.

(2) The use of Lamb's high summer and winter temperatures for 800-1950 AD and Mossman's temperatures to extend the Edinburgh record back to 800 AD.

(3) The use of Lamb's (1977) high summer wetness/ dryness indices and rainfalls as percentages of the 1916-50 averages for England and Wales for 800-1950 AD, to estimate precipitation for Scotland.

CHAPTER 3: CHANGES IN THE LIMIT TO CULTIVATION

INTRODUCTION

Having established a reliable record of past climate for Edinburgh and south-east Scotland, it is now possible to discuss the significance of past climatic changes on humans. One way in which climate affects humans is through its impact on agriculture. This chapter investigates how changes in climate over the last 800 years have affected agriculture in south-east Scotland. Specifically, this chapter aims to replicate M.L. Parry's (1972) classic study of 'Changes in the Upper Limit of Cultivation in South-East Scotland: 1600-1900 AD'. A replication of Parry's pioneering work seems necessary because: (1) more information is now available; and (2) problems exist in the original study.

PARRY'S WORK

Parry's (1972) classic study shed valuable light on the link between arable agriculture and climatic change. Parry initially analysed the physiological requirements of oats, which indicated that cultivation in the marginal lands of south-east Scotland was related to three factors: summer warmth, summer wetness and exposure. Given these relationships, Parry suggested that oats could not be cultivated unless they experienced more than 1050 day-degrees C above 4.4°C per year, a potential water surplus less than 60 mm and average wind speeds lower than 6.2 m/sec wind speed.

He then reconstructed summer warmth and wetness based on Lamb's trends of temperature and rainfall since the early Middle Ages. The results indicated that summer warmth changed over time and that as a result, the altitudinal limit for the cultivation of oats also varied. For example, the altitudinal limit of 1050 day-degrees C was at the high level of 450m between 1150-1250 AD, 400m between 1250-1450 AD and at only 310-325m between 1500-1650 AD. Calculated summer wetness revealed the following relationships. During the climatic optimum in the Middle Ages, 1150-1250 AD, there existed a low end-of-summer potential water surplus. Over the next two centuries, the potential water surplus rose by about 70mm as the climate became wetter. This trend was then temporarily checked, but continued after 1530 when there was a 10% increase in rainfall. Between 1650-1700, there was a particularly high frequency of especially wet autumns, which accentuated the effects of increasingly wet summers (Parry 1978).

Historical records of the dates at which farms were abandoned over these centuries showed remarkable agreement with the fluctuations of the 1050 day-degrees C altitudinal limit and the changes in the potential water surplus. Cold and wet periods saw farm abandonment while warm and dry periods saw farms established at higher altitudes.

THE IMPORTANCE OF PARRY'S WORK

Parry's work is important for many reasons. First, he emphasized the influential role which climate, both in the short-term and the long-term played in agriculture of the past. This view is in contrast to that of many historians, who maintain that there is little link between climate and human society.

Parry succeeded in reducing the widespread uncertainty which surrounded the role of climatic change in agricultural history, while recognizing the role of technological change. He focused upon secular climatic change occurring in particularly vulnerable areas, namely marginal maritime uplands. Here, even minor climatic changes can have an effect on human settlement out of all proportion to their apparent magnitude. This approach proved far more productive than earlier broad-correlational approaches. Furthermore, Parry's method could be used in other regions in England, Wales, Ireland, Iceland and Norway (Parry 1978).

Parry made a second major contribution to methodology. He developed a technique of mapping and dating the reclamation and reversion of the upper limit of cultivation through the use of aerial photographs. Prior to his work, there are very few references to air photograph analysis for this purpose (Parry 1973). Beforehand, researchers relied on observations in the field, an approach which has serious drawbacks, especially in areas of rough moorland and on documentary evidence, which is rarely either comprehensive or complete. Parry had hoped that he had developed a sensitive mapping technique that could be applied more widely to similar studies in the Highlands. Ian Shephard, Head of Grampian Archaeology, believes Parry achieved his goal and that it would be worthwhile trying to replicate Parry's work in another area - such as in

Grampian (writ. comm. 1989). Dodgshon, University College of Wales, also believes that there is scope for extending this technique of air photograph analysis to other areas (writ. comm. 1989).

Parry's approach was novel, in that he developed guidelines for interpreting and analysing an entire relict landscape. Parry observed the settlement changes that took place over the whole of the Lammermuir Hills of south-east Scotland. Prior to his work, the uplands were much ignored (Beresford 1951; Beresford et al. 1958; Harris 1968; Allison 1970 and Beresford 1971). Earlier researchers favoured empirical studies of specific features or sites with the focus on the abandonment of a single dwelling within a hamlet or village. So, Parry provided a much more complete and comprehensive view of settlement changes than had hitherto been produced.

A final feature of Parry's work was that it was inter-disciplinary in its approach. Parry utilized research methods from the fields of geography, archaeology, history, philology, climatology, phenology and economic history. Furthermore, the interpretation involved theory from disciplines such as geography, archaeology, economic history, climatology and agrometeorology. Today, it is the aim of much scientific research to collate material and theory from different academic fields. However, at the time of Parry's writing, interdisciplinary work was not generally undertaken.

CRITICISMS OF PARRY'S WORK

(1) ARCHAEOLOGICAL EVIDENCE

Although Parry's model has attracted wide interest and acclaim, it has also given rise to disquiet and debate. The major source of discontent is Parry's interpretation and dating of archaeological sites, most especially of the cultivation ridge (Barber pers. comm. 1989; Dodgshon writ. comm. 1989 and Tipping pers. comm. 1989). Many of Parry's basic assumptions are now being questioned by some researchers.

INTERPRETATION OF RIDGE-AND-FURROW LANDSCAPE

(1) Parry assumed that all ridge-and-furrow was necessarily a by-product of arable agriculture. Considerable doubt has been cast upon this conventional belief (Rowley et al. 1982) and it has been suggested that the wide high-backed rigs might be better interpreted as monuments, rather an relic features of arable farming (Cantor 1982).

(2) Parry assumed rigs were solely the product of the mould-board plough (Nightengale 1953). Even today, it is often asserted that the high ridges are the product of the plough and, indeed, Lerche's (1986) ploughing experiment proved that it was possible to produce significant ridges in only a few seasons. Despite this recent evidence, current opinion suggests that it was physically impossible to create the characteristic humped profile by continual ploughing and that ridge-and-furrow must have been deliberate and created by hand. The assymetrical ard, a prehistoric hand implement, appears to have been utilized to produce rigs at 15 Roman-Age sites and 18 Iron Age hill-forts and settlements (Bowden et al., 1989). Today, 'lazy-beds' (These are a type of cultivation rig found in

the Western Isles, Shetland, Orkney and the coasts of Ireland) are the produce of spade agriculture, as the rocky terrain makes the use of the plough impractical (Bell 1984). In Scotland, the 'cas dhireach' or straight space was used, in past times, for undercutting the turf and piling it up (Fenton 1985). Furthermore, it is suggested that the making of the aratral curve would have been extremely difficult and would have called for a wholly unnatural ploughing method (Rowley et al., 1982).

(3) Parry assumed that ridges were produced for drainage purposes, with water draining from the fields along the furrows (Orwin et al. 1958). Support for this argument may be seen in the actual arrangement of the rigs. On slopes greater than 5 degrees, the ridge-and-furrow runs at right angles, or nearly so, to the contours. Also, where there are natural water courses, ridges run at right angles to them, thereby facilitating the drainage of water (Rowley et al. 1982). In addition, the dry, sandy soils of the machair lands, which would not have needed surface drainage, never had ridge-and-furrow (Fenton pers. comm. 1991).

Further support for the drainage hypothesis comes from archival material. There is implicit acceptance of the idea in three quotations of Johnstone in 1794: (1) "the ridges and water furrows...the only method whereby drainage can be effectually accomplished". (2) "In most of the central counties of England and also in Flanders, the general mode of keeping land dry is by ploughing it up in high and broad ridges, from twenty to thirty, and even up to forty feet wide, with the centre or crown three or four feet higher than the furrows." and (3) "the ridges...it must be esteemed, for land of a very retentive surface, is an excellent mode of drainage."

However, the existence of rigs on chalk downs, limestone hills and dry gravel terraces, where no such drainage problem exists, casts doubt on the drainage theory (Rowley et al. 1982). He suggested that ridges developed as a way of draining land, but subsequently became the normal way of ploughing. Support for this hypothesis is also to be found in Johnstone (1794) who states: "they have been applied on dry loams most absurdly; and from being perhaps a custom in that part of the country, no discrimination has been made".

Alternatively, it has been suggested that rigs were produced so as to increase the surface area of the field, even if only by a small proportion (Bowen 1961).

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Alternatively, it has been suggested that rigs were produced so as to increase the surface area of the field, even if only by a small proportion (Bowen 1961).

(4) Parry assumed that the dimensions of the rigs were definite age indicators. In different periods, Scotland's peoples have used different ploughs and ploughing methods. The changing equipment and practices resulted in different shaped rigs. For example, Parry (1972) suggested that the introduction of the swing plough introduced level straight ridges, thus abandoning the earlier high-balk ridges. This is because the swing plough could turn a straight furrow more easily than the earlier Scotch plough, but could only operate on high-backed ridges with difficulty.

The dimensions of ridge-and-furrow may, in fact, be determined by the nature of the soil (Bell 1984). It has been suggested that the heavier the soil, the more amenable it is to large ridges. Some ridges measure up to 1.75m, from the depth of the furrow to the height of the ridge and are found on heavy midland clays (Rowley et al. 1982).

Archival material supports the landscape evidence. William Folkingham, a surveyor in the 18th century, recorded that strips were ploughed into ridges where there were "fat, strong, and fertile grounds that be tough, stiffer, binding cold and wet"; and that "narrower ridges (stitches) were recommended to cold and stiffe ground inclining to barrennesse". These stitches are common on the light grounds of Norfolk, Suffolk and Harfordshire (Beresford 1958). Despite the above evidence, Clark (1960) examined the relationship of soil type and ridge size and concluded that variations in ridge size were not caused by variations in soil type. For example, there did not appear to be a tendency for narrow ridges to occur in poorly-drained soils.

The dimensions of the ridges may have been determined by the length of time for which the ground was ploughed. It has been put forward that the largest ridges tend to be those which have been ploughed in the same fashion, over many decades (Rowley 1972; Rowley et al. 1982).

(2) CLIMATOLOGICAL RECORD

A second set of problems concerns Parry's climatological record. Finnish phenological data was used to establish a minimum level of warmth necessary for oat cultivation in Scotland. Finnish data is unlikely to be representative of Scottish conditions.

A REPLICATION STUDY : RECONSTRUCTING THE ALTITUDINAL SHIFT IN THE LIMIT TO CULTIVATION

A replication study of Parry's important work seems necessary because: (1) problems exist in the original study; and (2) more information is now available.

In order to link the temperature record with altitudinal limits to crop growth, temperatures were calculated for the growing season at an altitude of 320m, the climatic limit for successful oat cultivation in south-east Scotland (Parry 1978). The present growing season for oats is from April to the end of August, although oats are harvested as late as October, if there has been a lack of warmth (i.e. less than the required 1050 day-degrees C). Manley's temperature data (1974) are representative of sites at altitudes of 100-200 ft. The mean of 150 ft or 45.7m, was used as the base level for calculations. Temperature decreases by 1°C for every 82.4m of altitude in south-eastern Scotland (Birse and Dry 1970) and therefore, an altitudinal limit at 320m represents a temperature decrease of 3.3°C.

The temperature record established in Chapter Two is accurate; however, it is based only on high summer, winter and annual temperatures. This record is of sufficient accuracy for most studies. (Reliability was discussed earlier, in the Meteorological Descriptions of Chapter of Chapter 2, in reference to Lamb's work; the current work is based on Lamb's climatic data and therefore has a similar degree of reliability.)' In fact, this thesis, excluding this chapter, uses this record. It is possible to make it slightly more accurate by making further adjustments. Because the temperature difference varies seasonally between Edinburgh and central England, adjustments for seasonal differences can be made. Using the 132 year record of Mossman, Duncan (1991) has shown that Edinburgh is $0.9^{0}C$ cooler than central England in spring (March, April and May); $1.1^{0}C$ colder than central England in summer (June, July and August); and $0.8^{0}C$ cooler in autumn (September, October and November). Therefore, in order to estimate temperature in south-eastern Scotland in spring at 320m, it is necessary to subtract a figure of $4.2^{0}C$ from Manley's and Lamb's data. Similarly, $4.4^{0}C$ was subtracted from the summer temperatures and $4.1^{0}C$ from the autumn temperatures.

After calculating the temperatures of the growing months, it is possible to calculate day-degrees C. Day-degrees C are derived from the monthly mean temperature above a base temperature, multiplied by the number of days in the month. First, day-degrees C were calculated utilizing a base temperature of $4.4^{0}C$, the same value used by Parry in his original work. Then the exercise was repeated, using a base of $0^{0}C$, a preferred value among agrometeorologists (McKinley pers. comm. 1990). The results of this procedure can be seen in Table 3.1. When the $4.4^{0}C$ base is employed, no period contains a growing season with the required 1050 day-degrees C for oat cultivation at 320m. Even when the growing season is extended to encompass October, no year has sufficient accumulated warmth. When the $0^{0}C$ base is used, day-degrees C vary from 1257.8 to 1457.1. All crops would have been harvested in August, as opposed to October. This is more in accord with the harvest time, as defined by agrometeorologists.

The link between the altitudinal limit for oats and

Table 3.1

Calculated Day-Degrees C using a 4.4°C and 0°C Base

Period(AD)	Accum.Warmth(4.4°C Base)	Accum.Warmth(0°C Base)
800-1000	676.2	1334.6
1000-1100	948.1	1410.4
1100-1150	919.0	1399.0
1150-1200	998.0	1457.1
1200-1250	998.0	1457.1
1250-1300	998.0	1457.1
1300-1350	828.7	1355.7
1350-1400	851.7	1349.0
1400-1450	839.5	1360.3
1450-1500	887.8	1304.0
1500-1550	851.7	1349.0
1550-1600	723.3	1257.8
1600-1650	841.7	1270.1
1650-1700	826.4	1261.2
1700-1750	848.7	1346.9
1750-1800	827.3	1334.7
1800-1850	777.5	1313.8
1850-1900	836.1	1328.4

*When using the 4.4°C base, the growing season extended from April-October. When utilizing the 0°C base, the growing season extended from April-August. The latter is more realistic.

climate change was calculated in the following way. First, a calculation was carried out to establish the number of day-degrees C that are equivalent to a change of temperature of 1.°C. The result was 214 day-degrees C. Therefore, for a rise in the altitudinal limit of 82.4m, there is a decrease of 1°C and a decrease of 214 day-degrees C. The altitudinal limit at any one period is calculated from:

(the number of day-degrees C at the end of August minus 1050 day-degrees C) multiplied by 82.4/214, + 320.

Parry recognized that in addition to summer warmth, it is important to consider summer wetness as an influence on the altitudinal limit of cultivation. He established mean monthly rainfall and potential transpiration rates for the growing season. Parry assumed transpiration rates altered almost linearly with rainfall, believing that there was a close correlation between summer temperature and summer rainfall in Scotland. This does not appear to be correct. Comparison of Mossman's precipitation data and temperature data (1896), reveals that the correlation for summer temperature and summer precipitation is -.304; although this is sigificantly different from 0 at the p = 0.05 level (.946 for n = 100), only 9.24% of the variation is explained. Precipitation changes and their effect on the limit of agriculture will not be evaluated here.

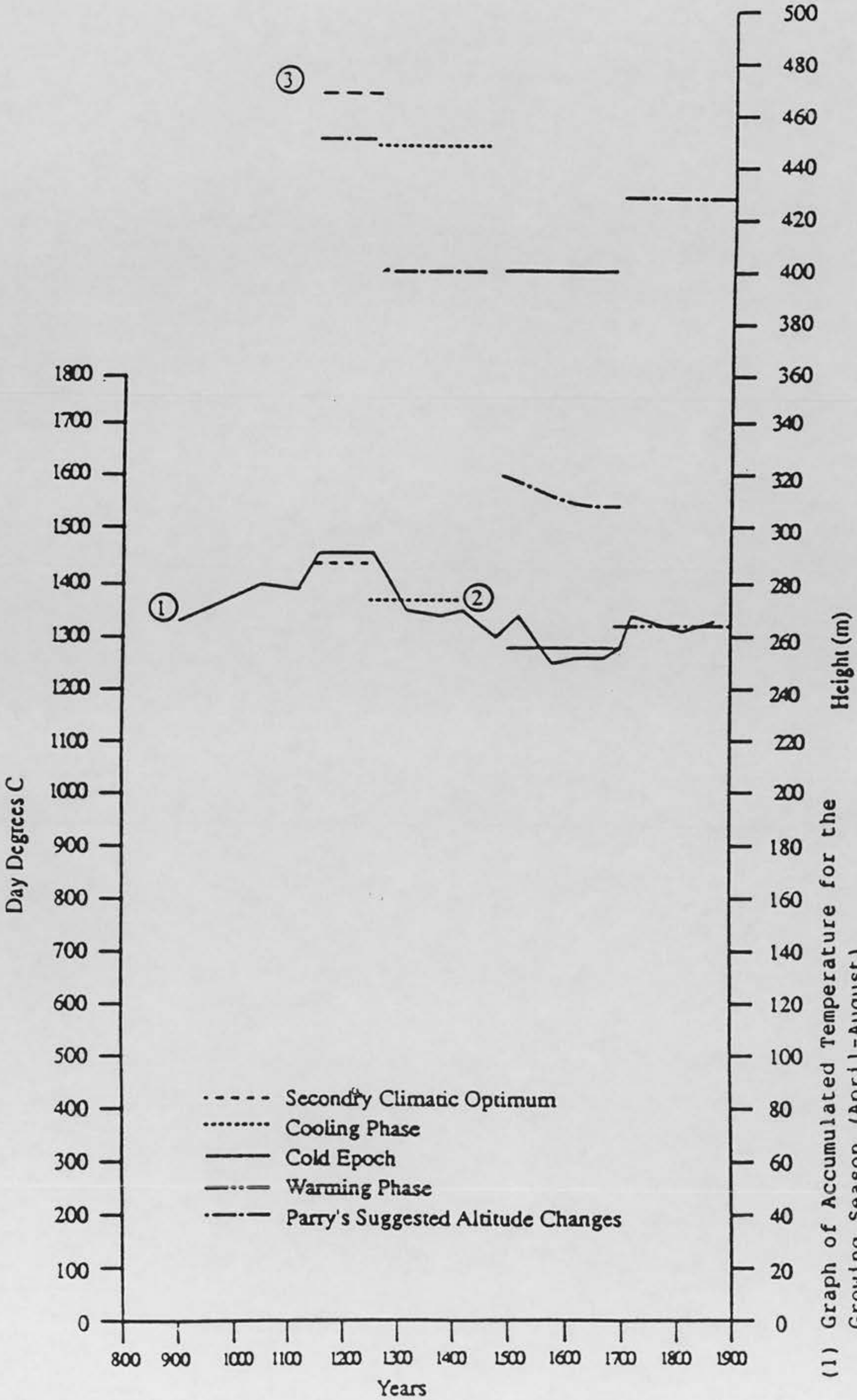
COMPARISON WITH PARRY'S RESULTS

The results of the new analysis can be seen in Table 3.2. A graphical display of the results can be seen in Figure 3.1. There are some differences between the results of this re-

The Altitudinal Shift in the Limit of Cultivation Table 3.2

Period(AD)	Agricultural Limit	Agreement with Parry
800-1000	429.6	
1000-1100	458.8	
1100-1150	454.4	
1150-1200	476.8}	This figure agrees with
1200-1250	476.8}	Parry's value (i.e.>450).
1250-1300	476.8]	
1300-1350	437.7]	No agreement. Parry found a
1350-1400	435.1]	fall of 50m; a fall of 19.6m
1400-1450	449.5]	was calculated here.
1450-1500	417.8	
1500-1550	435.1)	No agreement. Parry found a
1550-1600	400.0)	fall of 75-90m; a drop of 39.1m
1600-1650	404.8)	was found here.
1650-1700	401.2	
1700-1750	434.3}	
1750-1800	429.6}	Parry does not provide a
1800-1850	421.6}	value for this warming phase.
1850-1900	427.2}	

Fig. 3.1



(1) Graph of Accumulated Temperature for the Growing Season (April-August)
(2) Graph of Mean Accumulated Temperature for Each of Parry's Periods
(3) Graph of Altitudinal Shifts for Corresponding Periods

evaluation and Parry's work. For the secondary climatic optimum, 1150-1250 AD, the limit of cultivation stands at 477m. This figure is in accord with Parry's limit of >450m. For the cooling phase, 1250-1450 AD, the re-evaluated agricultural limit falls by 36m to 441m. Parry, however, calculated a fall of 50m. For the cold epoch, 1500-1650, the re-evaluated limit fell a further 39m, down to 402m. In contrast, Parry estimated a fall of 75-90m for this late medieval cooling. During the warming phase of 1750-1850, the re-evaluated limit again increases and rises by 26m to 428m. Parry does not provide a value for this warming phase.

Three possible explanations may account for the discrepancies between the two reconstructions. First, Parry did not adjust the English data for latitude. Therefore, Parry's temperatures would have been at least 0.9, 1.1 and 0.8^{0}C too high in the spring, summer and autumn months, respectively. These higher temperatures allowed sufficient warmth for growth at 320m between 1200-1400 AD and 1800-1900 AD. The lowering of seasonal temperatures prohibited sufficient warmth for oat cultivation at 320m.

Second, it appears that Parry used a lapse rate of 103 day-degrees C, for every increase in altitude of 82.4m. In order to produce a lapse rate of 103 day-degrees C, Parry appears to have assumed that the growing season ended in mid-July in the historical period (Edinburgh and South of Scotland Schoolof Agriculture pers. comm. 1990). Oats cannot be harvested until the end of August, if not the end of October. The agricultural department at the University of Edinburgh finds such a rate far too low and supports the 214 day-degrees C value. Therefore, it appears that all Parry's altitudes have been over-estimated. For example, when the average temperature fell by over a degree centigrade between 1300-1600 AD, Parry proposed a shift in the altitudinal limit of 150m; whereas, this study yields a shift of 75m.

Finally, as discussed above, Parry utilized precipitation data; whereas, the present author did not. This does not mean that the present study is lacking in this respect. Marginal land in the British Isles has been mapped using only accumulated warmth (Parry 1978). Furthermore, Parry's assumption, that summer precipitation and summer temperature are closely related in Scotland, is erroneous. The present study did not make the same assumption.

SUMMARY

This model suggests that the cultivation limit has shifted 75m over the past 800 years. It is higher than calculated by Parry and it fluctuates by only half the amount calculated by Parry.

INDEPENDENT EVIDENCE

Evidence of former tillage/settlement may provide supporting evidence for the newly-established model. This evidence includes the study of: (1) the relict landscape and (2) place-names. Parry chiefly used ridge-and-furrow as evidence for his study. Ridge-and-furrow will not be used here because of the problems associated with their analysis, as described earlier in this chapter.

THE RELICT LANDSCAPE: CAIRNS

Cairns consist of stones and boulders collected from the land. Various uses have been assigned to the cairn, Scotland's most ubiquitous field monument. It has been suggested that many mounds of stone and other debris were cleared from areas, which were to be used for cultivation (Fowler 1984). However, it has been argued that some cairns were not related to agriculture at all. Cairns, which often contain evidence of human remains, may have been strictly for burial. Because these cairns often dominate a hilltop or skyline, it is suggested that these mounds mark the burials of chieftains; and that these cairns were associated with the chiefdoms in the nearby fertile valleys (Baldwin 1985).

With respect to the above controversy, Jobey (1974) wrote 'the chief difficulty with respect to the majority of assemblages (cairns)...is the impossibility on present evidence of making a certain attribution to either category, sepulchral or agricultural, or to distinguish those situations where both may be present'. Fowler (1984) suggested that it was likely that prehistoric peoples did not make such a clear-cut distinction between the practical and the sacred, as is common in modern western society and that ultimately, there is probably an element of agricultural clearance in funerary architecture.

It is assumed here, after Fowler (1984), that cairns probably had both agricultural and sepulchral uses. Therefore, a survey of the cairns in the study area may provide an indication as to the altitude at which prehistoric peoples farmed.

A survey of the 36 cairns in the study area indicated that they occurred at altitudes as high as: 398; 400 (Rutherford's Cairn); 400 (Mutiny Stones Long Cairn); 400; 410; 410; 420; 430; 430; 440; 447 (Twinlaw Cairns); 460 and 480m (Titling Cairn). The altitudes show a definite bi-modal distribution. 80.6% of the cairns were found between 250-480m, with a mean altitude of 350m. 19.4% were found lower than 240m, with an average height of 205m.

The two different distributions may represent two different periods of farming. Cairns have been absolutely and relatively dated. Carbon-14 dates have been obtained from graves, which contain carbonized material, found within cairns (Fowler 1984). Relative dates have been estimated from: (1) pottery, which can be distinguished in form and decoration in each succeeding century or two, found within cairns; and (2) the physical characteristics of cairns, which can eb somewhat distinguished in size and shape through time (Tipping pers. com. 1989). Cairns were in use from the Neolithic through to the Iron Age (or 3500 BC - 0 AD). They then disappeared at the time of the introduction of the mould-board plough, as they had become redundant, at about 1250 AD (Parry 1972). Cairns are re-introduced at the time of improvement, when rigs go out of use (Parry 1972). The Mutiny Stones Long Cairn dates to about 2000 BC; whereas, Twinlaw Cairns date to after 1000 BC (Baldwin 1985). Additionally, many round cairns, dating from c.1000 BC, litter the highest ridges of the

Cheviots. In light of the dates provided, it is suggested that the majority of cairns date to the prehistoric period. The minority may date to post-improvement times, as they are found near the modern-day lower limit of successful oat cultivation of 250m.

Given that the cairns may be archaeological evidence for past agriculture, it is necessary to examine the climatic evidence, in order to make the climate-agriculture link. Lamb (1977) has shown that temperatures during the Sub-Boreal (2500-900 BC) in Britain, were as high as 10.0°C. Temperatures in the Sub-Atlantic (900-450 BC) fell by 0.7°C to 9.3°C. The temperature of the Sub-Boreal of 10.0°C, is virtually the same as the temperature of the Medieval Warm Epoch, namely 10.1°C. The Sub-Atlantic temperature, 9.3°C, is equivalent to the low temperature experienced at the beginning and at the end of the Little Ice Age. However, Renfrew (1974) suggests Sub-Atlantic temperatures were slightly warmer and closer to those experienced at the close of the Medieval Warm Epoch, i.e. 9.5°C. (All temperatures refer to England, and therefore must be adjusted appropriately for Scotland).

If the proposed dating scheme of cairns and Lamb's temperatures are accepted, then the following is apparent. First, neolithic farming occurred at altitudes of at least 400m (Mutiny Stones). It is likely that agriculture occurred at even higher altitudes, but the archaeological record is limited. As previously mentioned, cairns, perhaps neolithic cairns, have been found as high as 480m. This altitude is virtually the same as the present study's

Medieval Warm Epoch cultivation limit. Both the Neolithic and the Medieval Warm Epoch experienced the same temperatures, and hence the same cultivation limits would be expected. The evidence, though sparse, is in good agreement with this study's limits.

Twinlaw Cairns dated at 1000 BC, found at 447m, provide evidence that farming may have occurred as high as 450m during the equally cold Little Ice Age. This is certainly higher than the present study's limit of 400m.

In summary, cairns provide evidence that farming may have been taking place at altitudes of over 400m, throughout the Neolithic to Iron Age. Temperatures for these periods are similar to those experienced from the Medieval Warm Epoch to the begining of the Little Ice Age. It seems reasonable to assume, therefore, that if farming took place at altitudes of over 400m throughout the prehistoric period, it is most likely that arable agriculture took place at similar altitudes in the historic period. This supports the present work which finds arable agriculture above 400m for the historical period.

PLACE-NAME EVIDENCE

The philological record has been dismissed as evidence of past cultivation in south-east Scotland for several reasons. First, the record is scant. Second, it is difficult to interpret the anglicised 'gaidhlig' place-names, as shown by Milne's (1912) study of East Lothian and by Johnston's (1940) study of Berwickshire. Third, only a broad picture of population movements can be inferred from the place names (Nicolaisen 1987). Fourth, the date of the place-name is often difficult to obtain. And last, it is impossible to assess the number of corrupt or missing field names from the philological record.

In spite of these difficulties, this study will examine the place-name element 'rig', as evidence of the past limits of cultivation in south-east Scotland. The term rig is definitely related to areas of former arable agriculture; it was chiefly used as 'An extent of land, long rather than broad, used for cultivation, a strip, a field'. The name rig has less of the difficulties associated with it than other place names. It is commonly used and it sidesteps the problem of anglicised 'gaidhlig' place names. Although rig still only provides a broad picture of population movements, this is all that is required in the present work. Rig was commonly in use, as early as 1300 AD.

In total, 36 names containing rig were found. The altitude of each name was then recorded. Three rig-names were found at or above 400m: East Rig 400m; Blythe Rig 431m and Newbigging Rig 400m. The altitudes were then grouped in classes. Like the cairns, there was a definite bi-modal distribution. 41.7% of the rig names were found above 300m with a $\bar{x}$ of 343.7m; 58.3% were under 250m with a $\bar{x}$ of 205m.

The presence of the place-name element at altitudes of over 400m suggests that arable farming took place at heights of over 400m. These sites most probably post-date 1300 AD, as the place-name element was not commonly in use until this time. The presence of one name at 431m supports the present study's limit of 440m for the period 1250-1400 AD.

Also noteworthy, is the fact that the rig-names and cairns show a similar distribution: the $\bar{x}$ altitude of the rigs is 343.7m; whereas, the $\bar{x}$ altitude of the cairns is 350m. This is probably to be expected, as the two time periods experienced similar temperatures and hence, would have had similar limits to cultivation. The 'historic' cairns and low rigs, again show a similar distribution, with a shared $\bar{x}$ of 205m. This may be interpreted as (1) evidence of post-rig cultivation, as the altitude is close to the modern, lower limit of successful oat cultivation or (2) merely coincidence.

CONCLUSIONS

The implications of this study are that the upper limit of cultivation does shift in relation to secular climatic change as Parry suggested. This study shows that the cultivation limit has shifted 75m over the past 800 years. Analysis of independant evidence supports this limit. Climate is an important factor affecting the course of agricultural change alongside socio-economic factors. These factors would include: technology and farming practices; land ownership and land tenure; accessibility of the Uplands to inputs and markets and population.

The present study has provided a new and more reliable methodology for calculating accumulated warmth for the growing season and for calculating the altitudinal shift in the cultivation limit. The present work has also shown that Parry's assumption that summer precipitation and summer temperature are closely related in Scotland is erroneous.

CHAPTER 4: CLIMATE AND DISEASE

INTRODUCTION

As previously established, secular climatic change is likely to have been influential in determining shifts of rural cultivation. Climate is also likely to have been an important factor in the spread of disease, especially of epidemic disease (Post 1983 a,b).

This chapter investigates the complex relationships that exist between climate and disease. Specifically, this chapter examines the relationships between climate and (1) plague; (2) malaria and (3) ergotism and the Scottish witch-hunts. These diseases differ according to their scale of impact. Plague decimated the population of fourteenth century Scotland; malaria affected the farming population of south-east Scotland; and ergotism, some authors suggest, may have been responsible for the deaths of over six thousand 'witches' throughout Scotland.

The approach used is to take historical records of occurrences of these diseases and to compare their trends with the reconstructed climate record. The possible influence of long-term climate on the spread of plague is investigated. The effects of long-term, medium-term and short-term climatic influences on malaria, are examined. The relationship of medium-term and short-term climate with ergotism and the Scottish witch-hunts is investigated.

THE POSSIBLE INFLUENCE OF CLIMATE ON PLAGUE IN SCOTLAND

The 1340s ushered in one of history's most infamous rat-borne pandemics - the Black Death (Hendrickson 1983). This 'Destroying Angel' reached Scotland in 1349. The Scottish people and indeed all Europeans, blamed clouds or miasmas arising from the earth, volcanic eruptions, earthquakes, comets, cats, dogs, drunkards, gravediggers, cripples, strangers, gypsies, beggars, lepers and Jews for the 'Great Dying' (Hamilton 1981).

Today, disease is seen as a product of the interaction between a disease agent, a disease host and the environment (Brandford 1977). In the case of bubonic plague, the agent is the bacillus, Yersinia pestis and the host is the rat, Rattus rattus, or man (Hendrickson 1983).

The relationship between the disease agent and disease host is well understood. Bubonic plague is caused by the invasion of a rat by Y.pestis. The bacillus multiplies rapidly in the infected animal; thus, when a rat flea, X. cheopis, feeds, it sucks up large numbers of bacteria from its blood meal. The bacteria multiply rapidly in the flea's stomach until it is completely filled. Because no more blood can pass the flea's blocked stomach, the flea continues to feed, but eventually regurgitates infected blood. The flea also defecates as it feeds. As soon as the rat dies, the fleas search out alternative hosts, rat or man. Thus, Y.pestis is emitted onto the victim's skin and the bacteria enter into the circulation via the new puncture wound. Once bubonic plague becomes rampant amongst humans, another clinical form, pneumonic plague, may develop. This form of the disease is spread by droplet infection (Shrewsbury 1977).

The role of environmental factors is less well understood than the disease agent and disease host. Various environmental factors have been proposed to explain the spread of plague in Scotland; these include over-crowding of towns, simple housing, poor sanitation and climate (Hamilton 1981). Historians have favoured those explanations involving over-population and the inadequate disposal of refuse, to the virtual exclusion of climatic factors. When climate is invoked as a causal variable for the great pestilence, there has generally been no testing of the assumption. For example, Hamilton (1981) stated that Scotland's immunity to the plague until 1349 was due to her slightly cooler climate, which did not encourage the rats which spread the plague.

Climate exerts a major influence on the spread of bubonic plague. The Plague Research Commission (1908) concluded that the spread of rat and human plague is checked by temperatures over 26°C; this is because the plague-transmitting power of the individual flea is reduced. Furthermore, the disease cannot exist in epidemic form at temperatures over 27°C, as the flea's stomach block is dissolved. Bacot (1911-14) demonstrated that a temperature range of 20-25°C was the most suitable for the development of X.cheopis at all stages. Cold temperatures, as well as warm temperatures, also check plague. The Plague Research

Commission (1908) showed that low temperatures (i.e. those under 10°C) limited outbreaks. First, this is because infected rats died more quickly with fewer plague bacilli in the blood; thus, fewer fleas had the opportunity to acquire the infection. Second, low temperatures limit the vector efficiency and the general activity of the rat fleas. Third, healthy rats die more quickly at cool temperatures. Last, Bacot (1911-14) demonstrated that X.cheopis will not breed at all in cold weather; in cool weather, the breeding of a perfect insect may take months. Furthermore, the eggs of X.cheopis will not hatch below 12.8°C.

Moisture, like temperature, also limits plague. St. John Brooks (1917) showed that plague cannot maintain itself when the air is very dry. It has also been shown that excessively high humidity is adverse to plague (Hirst 1953).

In summary, the macro-climate plays an important role in plague transmission, but so too do the various micro-climates. The temperatures and humidities of rat burrows, clay walls, straw roofs and slum huts will all affect the transmission of plague to varying degrees (Learmonth 1988). This chapter limits itself to the examination of the macro-climatic influence only.

In view of the past failure to examine critically the effect of climatic influences on the spread of plague in Scotland, this section aims to investigate the relationship. Specifically, the work (1) demonstrates that Scotland's climate prior to 1349 was not too cool to discourage rats, but in fact was too warm and dry for the fleas to survive; (2) provides an explanation for why plague continued to persist into the Little Ice Age, despite the climatic downturn and (3) explains why plague may never have occurred in the west and north of Scotland.

METHOD

In order to investigate the relationship between climate and plague, a comparison was made between the climate of years with plague and of those without. Before explaining the method used here, it is important to stress the limited documentary evidence available for studying pre-seventeenth century plagues in Scotland. Due to the limitations of the sources, it is difficult to ascertain the scale and mortality of most outbreaks. Also, it is difficult to establish which were the most severe outbreaks in the 14th, 15th and early 16th centuries.

The mean monthly temperature record for Edinburgh for 800-1900 AD, by Duncan (1991), was utilized as the temperature record (see Chapter Two). Scotland experienced four major pestilences in 1349, 1362, 1380 and 1392. Plague continued to erupt in isolated towns and rural areas throughout the 15th-17th centuries (These dates are from Shrewsbury (1977), as are the given dates onpages 96 and 97. Shrewsbury's work was used because it contains the most comprehensive listing of plague epidemics), but the outbreaks were limited both in time and space (Shrewsbury 1977). Again, it is important to recognize the limitations of the sources. Because documentation relating to plague outbreaks in Scotland is far more abundant for urban than for rural areas, outbreaks may not have been limited in time and space. Thus, the climate of the plague period, 1350-1400 AD, was compared with the climate of the Medieval Warm Epoch (MWE) period, 1150-1300 AD, when there were no recorded plagues.

In order to determine if the Medieval Warm Epoch was too warm and dry to support the fleas that carried the Yersinia bacillus, the following procedure was undertaken.

Edinburgh's 1951-1980 mean monthly maximum temperature was used to predict monthly maximum temperatures for the historical period. This is because Edinburgh's present mean annual temperature of 8.7°C, was the same as Edinburgh's mean annual temperature for 1350-1400 AD. In order to determine the maximum temperatures attained in that period, Edinburgh's 1951-1980 mean monthly temperatures were compared with mean monthly maximum temperatures for the same period. This determined the differences, which were then established in relation to the 1350-1400 AD monthly temperatures. Lamb's (1977) summer wetness/dryness index was utilized to determine the amount of moisture for this time period.

Next, the relationship between the plague outbreaks of the 15th-17th centuries and the cool climate was examined. Plague years were checked against Lamb's (1977) winter mildness/severity and summer wetness/dryness indices.

Lastly, the relationship between climate and the location of plague outbreaks was investigated. This involved several steps. First, centres of plague outbreaks were mapped, for the period 1350-1650 AD. Second, plague-time temperatures for the Highlands and west were calculated. To determine the temperature in the Highlands in 1350-1400 AD, the following procedure was undertaken. First, taking Nairn to be representative of a Highland weather station (The Meteorological Office 1989), a comparison was made between Nairn's mean monthly temperature and Edinburgh's average monthly temperature, for the period 1951-1980. (For these years, Edinburgh, with a mean annual temperature of 8.7°C, is 0.5°C warmer annually than Nairn, with an average annual temperature of 8.2°C (The Meteorological Office 1989). Second, the difference between the two sets of figures was then either added or subtracted from the long term record for Edinburgh 1350-1400 AD. The differences between the two weather stations are assumed to have remained constant. Third, the temperature at 100m a.s.l. was calculated, in order to determine maximum temperatures in the Highlands. The same procedure was also carried out for Tiree, in order to obtain representative statistics for the west of Scotland.

RESULTS

Table 4.1 shows the temperatures of the plague period of 1350-1400 AD and the temperatures of the preceding MWE non-plague period of 1150-1300 AD. Table 4.2 shows the maximum temperatures attained in the plague period. Table 4.3 gives Lamb's (1966) figures for high summer rainfall

Temperatures of the Plague Period (1350-1400AD) and the Temperatures of the Preceding MWE Non-Plague Period (1150-1300AD) in Edinburgh and South-East Scotland

Table 4.1

Month	For the Period 800-1000 AD Temperature(°C)	For 1000-1100 AD
J	2.5	2.7
F	3.3	3.6
M	4.5	4.8
A	7.2	7.5
M	10.2	10.6
J	13.7	14.2
J	15.3	15.9
A	14.9	15.4
S	12.4	12.9
O	8.6	8.9
N	4.8	5.1
D	2.3	2.5

	For 1100-1150 AD	For 1150-1200 AD
J	2.5	3.2
F	3.4	4.1
M	4.6	5.2
A	7.4	7.9
M	10.5	10.9
J	14.2	14.5
J	15.9	16.1
A	15.5	15.7
S	12.9	13.2
O	8.9	9.3
N	5.2	5.6
D	2.3	3.0

	For 1200-1250 AD	For 1250-1300 AD
J	3.1	3.2
F	4.0	4.1
M	5.2	5.2
A	7.9	7.9
M	10.9	10.9
J	14.5	14.5
J	16.1	16.1
A	15.7	15.7
S	13.2	13.2
O	9.3	9.3
N	5.5	5.6
D	2.9	3.0

For 1300-1350 AD

J	2.8
F	3.6
M	4.8
A	7.5
M	10.5
J	14.0
J	15.6
A	15.2
S	12.7
O	8.9
N	5.1
D	2.6

For 1350-1400 AD

2.8
3.6
4.8
7.4
10.3
13.7
15.3
14.9
12.5
8.7
5.1
2.6

For 1400-1450 AD

J	2.4
F	3.6
M	4.4
A	7.1
M	10.5
J	14.0
J	15.2
A	14.8
S	12.3
O	8.5
N	4.7
D	2.1

For 1450-1500 AD

2.5
3.3
4.5
7.1
10.0
13.4
15.0
14.6
12.2
8.4
4.8
2.3

For 1500-1550 AD

J	2.8
F	3.6
M	4.8
A	7.4
M	10.3
J	13.7
J	15.3
A	14.9
S	12.5
O	8.7
N	5.1
D	2.6

For 1550-1600 AD

2.2
3.0
4.2
6.8
9.7
13.1
14.7
14.3
11.9
8.1
4.5
2.0

For 1600-1650 AD		For 1650-1700 AD
J	2.2	2.1
F	3.0	2.9
M	4.2	4.1
A	6.8	6.7
M	9.8	9.7
J	13.2	13.2
J	14.8	14.8
A	14.4	14.3
S	12.0	11.9
O	8.2	8.1
N	4.5	4.4
D	2.0	1.9

For 1700-1750 AD		For 1750-1800 AD
J	2.7	2.4
F	3.5	3.3
M	4.7	4.4
A	7.3	7.1
M	10.3	10.1
J	13.7	13.7
J	15.3	15.3
A	14.9	14.9
S	12.5	12.4
O	8.7	8.5
N	5.0	4.7
D	2.5	2.2

For 1800-1850 AD		For 1850-1900 AD
J	2.5	2.8
F	3.3	3.6
M	4.5	4.8
A	7.1	7.3
M	10.0	10.2
J	13.4	13.6
J	15.0	15.1
A	14.6	14.7
S	12.2	12.3
O	8.4	8.6
N	4.8	2.1
D	2.3	2.6

Table 4.2 Edinburgh's Calculated Mean Monthly Maximum Temperatures for 1350-1400 AD

	Edin.'s $\bar{X}$ Monthly Temp. (1951-1980)	$\bar{X}$ Monthly Max Temp.	Difference (Col.1-Col.2)	$\bar{X}$ Monthly Max. 1350-1400
J	3.3	11.6	8.3	11.1
F	3.5	11.4	7.9	11.5
M	5.2	13.7	8.5	13.3
A	7.4	17.6	10.2	17.6
M	10.2	20.6	10.4	20.7
J	13.2	23.4	10.2	23.9
J	14.7	23.3	8.6	23.9
A	14.5	23.1	8.6	23.5
S	12.7	21.1	8.4	20.9
O	9.9	18.3	8.4	17.1
N	5.8	14.3	8.5	13.6
D	4.3	12.4	8.1	10.7

Table 4.3 Lamb's (1977) High Summer Rainfall Wetness/Dryness Index

High Summer Rainfall as a % of 1916-50 $\bar{X}$ in England and Wales

1150-1300 AD = 85.3 %
1350-1400 AD = 105%

High Summer Wetness/Dryness Index

1150-1300 AD = 8.8
1350-1400 AD = 10.9

Note: No precipitation information exists for Scotland

for 1150-1300 AD and 1350-1400 AD; the high summer wetness/ dryness index is also presented for the same periods. Table 4.4 presents a comprehensive listing of Scotland's plagues along with Lamb's (1977)winter mildness/severity and summer wetness/dryness indices. Figure 4.1 maps all the centres of plague outbreaks for the period 1350-1600 AD. Table 4.5 and Table 4.6 show the temperatures in the Highlands and west for the 1350-1400 AD and 1550-1600 AD periods, respectively.

DISCUSSION

On comparing the plague period of 1350-1400 AD and the Medieval Warm Epoch non-plague period of 1150-1300 AD with their respective climates, the following is apparent. Plague did not occur in the early warm period, but in the slightly cooler, later period. This finding is in direct conflict with Hamilton's (1981) statement about Scotland prior to 1348; that is, that the 'slightly cooler climate did not encourage the rats that spread the plague'.

In order to explain this finding, the mean maximum monthly temperatures and measures of humidity were examined. The 1350-1400 AD summer monthly maximum temperatures (23.4, 23.3, 23.1 and 21.1^{0}C) all fell within the temperature range of 20-25^{0}C. Bacot (1911-1914) showed that this temperature range was the most suitable for the development of X.cheopis (the fleas that most efficiently transmit the Yersinia bacillus), at all stages. The Medieval Warm Epoch's mean summer temperature was warmer by 0.8^{0}C than the average summer temperature of the 1350-1400 AD period.

Table 4.4 A Comprehensive List of Scotland's Plagues and Lamb's (1977)Winter Mildness/Severity and Summer Wetness/Dryness Indices

Plagues	Winter	Summer
1348	+2	10.5
1392	-2	11
1402 Stirling, Dundee	-3	11
1420	+4	7
1431 Edinburgh 1432 Haddington	-12	12
1475 Edinburgh	+3	8
1493 1498	-5	16
1505 Edinburgh	+7	7
1512		
1513 Dene	-2	7.5
1519 Edinburgh, Lothian		
1529 Edinburgh	+2	11
1546 Aberdeen		
1548 Perth	-2	8
1549 Edinburgh, Aberdeen, Stirling, Haddington, Berwick		
1580		
1584 Perth, Dysart, Kirkcaldy 1586 Dundee, Niddrie, Dunse	-7	12.5
1587 Leith, Edinburgh		
1597 Esk Valley, Dalkeith, Newbattle, Inveresk, Musselburgh, Dolphinton, Ednam, Sprouston, Lyntoun	-5	11
1600 Findhorn, Morayshire?, Dundee, Craill, Eglesham, Eastwood, Glasgow		

1602	Edinburgh		
1604	Edinburgh		
1606	Edinburgh, Stirling, Dundee, Perth, Glasgow		
1607	Edinburgh, Stirling	-10	11.5
1608	Dundee, Perth		
1609	Perth, Kinghorn, Inverkeithing		
1624	Edinburgh	-7	13
1635	Preston, Prestonpans	-5	11
1637	Nisbet Mill		
1644	Edinburgh, Borrowstouness, Kelso, Perth		
1645	Edinburgh, Glasgow, Paisley, Lanark, Peebles Leith, Perth, Falkirk, Stirling, Dunfermline, Dysart, Galashiels		
1647	Brechin, Inverbervie, Largs, Dunblane, Menmuir, Aberdeen	-3	11
1648	Glasgow, Montrose		

Derived from Lamb(1977) and Shrewsbury(1977)

Note: Winter Mildness/Severity=The number of unmistakingly mild months (D,J,F)minus the number os severe months (D,J,F)per decade.

High Summer Wetness/Dryness=Each July or August with unmistakable evidence of frequent rains=1, an unremarkable July or August=.5, and a dry month=0.Totals per decade.

Fig. 4.1 Plague Centres of Scotland

Source: Derived from Shrewsbury

Table 4.5 The Temperature in the Highlands 1350-1400 AD and 1550-1650 AD

Nairn 1951-80	Edinburgh 1951-80	Difference 1951-80	1350-1400 AD 100 m a.s.l.	1550-1600 AD 100 m a.s.l.
J 2.9	3.3	- 0.4	1.2	0.6
F 3.8	3.5	+ 0.3	2.8	2.1
M 4.9	5.2	- 0.3	3.3	2.7
A 6.8	7.4	- 0.6	5.6	5.0
M 9.6	10.2	- 0.6	8.5	7.9
J 12.5	13.3	- 0.8	11.7	11.2
J 13.6	14.7	- 1.1	13.0	12.4
A 13.7	14.5	- 0.8	12.9	12.3
S 11.9	12.7	- 0.8	10.5	9.9
O 9.9	9.9	0	7.5	6.9
N 5.4	5.8	- 0.4	3.5	2.9
D 3.9	4.3	- 0.4	1.0	0.4

Table 4.6 The Temperature in the West 1350-1400 AD and 1550-1600 AD

Tiree 1951-80	Edinburgh 1951-80	Difference 1951-80	1350-1400 AD	1550-1650 AD
J 6.3	3.3	+ 3.0	5.8	5.2
F 6.4	3.5	+ 2.9	6.5	5.9
M 6.1	5.2	+ 0.9	5.7	5.1
A 7.0	7.4	- 0.4	7.0	6.4
M 9.7	10.2	- 0.5	9.8	9.2
J 12.3	13.3	- 1.0	12.7	12.1
J 13.5	14.7	- 1.2	14.1	13.5
A 13.2	14.5	- 1.3	13.6	13.0
S 11.5	12.7	- 1.2	11.3	10.7
O 9.4	9.9	- 0.5	8.2	7.6
N 6.4	5.8	+ 0.6	5.7	5.1
D 6.2	4.3	+ 1.9	4.5	3.9

Unfortunately, there was no way of accurately predicting the Medieval Warm Epoch's summer mean maximum monthly temperatures, because no climatic data exists for a summer mean of 15.9°C in Edinburgh. However, if the same differences (i.e. mean maximum monthly temperature - mean monthly temperature) are used, the results are as follows: 24.4; 24.7 and 24.3°C. These temperatures probably under-estimate the true temperatures, because with an increase in mean monthly temperature, there would be an accompanying rise in mean maximum monthly temperatures. Thus, temperatures exceeding 25°C probably occurred. The Plague Research Commission (1908) showed that the disease cannot exist in epidemic form at temperatures over 26°C. Furthermore, if temperatures rise to 27°C, the stomach block is dissolved (Hirst 1953). Therefore, it appears that the temperatures of the Medieval Warm Epoch may have been too warm to maintain an epidemic. This claim may be difficult to accept, as the Black Death appears to have originated in countries whose climates were substantially warmer than those of Britain. However, plague does not erupt in these warmer countries unless temperatures are considerably depressed (Hirst 1953).

Warm temperatures and dryness of the air are adverse to plague epidemics. Brooks (1917) pointed out that a great increase in the drying power of the air alone, might bring an epidemic to an end, even if the temperature never rose above 26°C. Table 4.3 clearly shows that the Medieval Warm Epoch was much drier than the following plague period.

Thus, the Medieval Warm Epoch's climate, with its warm temperatures and dry air, was not conducive to plague epidemics. In summation, it is suggested that temperatures in the period preceding 1349 were not too cool to support rat populations; as rats are likely to have flourished in these conditions. However, it was too warm and dry to support X.cheopis fleas, which harboured the disease. This is not to suggest that climate alone prevented plague in this period. Other factors surely played a role in the prevention of the disease.

Plague continued to erupt between the 15th - 17th centuries, despite the climatic downturn of the Little Ice Age (LIA). Table 4.4 shows that winters became more severe from 1550 onwards and summers became increasingly wet from the 1580's. Table 4.1 shows the temperatures of this cold plague period of 1550-1650 AD.

Bacot (1911-1914) showed that in cool weather, the breeding of fleas may take months (up to 182 days) for some species. Furthermore, he demonstrated that the eggs of X.cheopis do not hatch below 12.8°C. In the 1550-1650 AD period, fleas could not have hatched until June and they may not have matured for months. Even if fleas did mature, plague could not have sustained itself beyond September. The Plague Research Commission (1908) showed that with temperatures below 10°C, infected rats die more quickly with fewer plague bacilli in the blood; thus, fewer fleas have the opportunity to acquire infection. Even healthy rats die more quickly at cool temperatures (Hendrickson

1983). In addition, low temperatures influence the vector efficiency and general activity of rat fleas (Hirst 1953). Thus, low temperatures check plague.

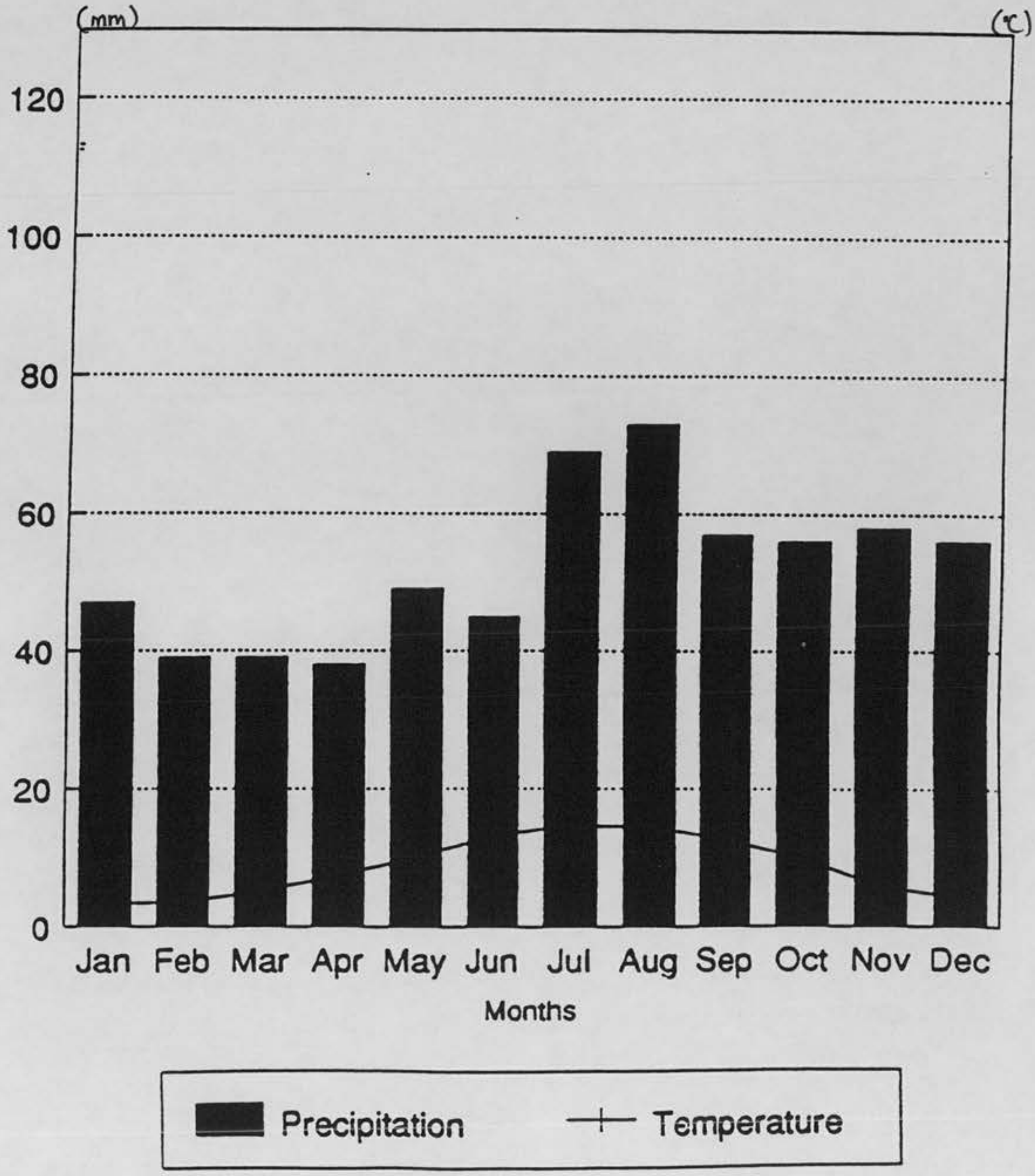
Despite the Little Ice Age's low temperatures check on plague, the disease continued to occur. Figure 4.1 shows the distribution of plague centres. Most centres were sea or river ports. One possible explanation is that cargo ships could have carried plague rats, which could have escaped into the towns. X.cheopis could easily have survived on the rats who migrated to warm households. Plague could never have spread to neighbouring towns. as the severe climatic conditions prevented the spread of rats and their fleas. Also, the cold winter temperatures of the LIA prevented plague from persisting from one year to the next. Only in 1607, 1608 and 1644 did plague carry over into the following year (inferred from Table 4.4). It is likely that the winters did stop plague, but maritime influences are likely to have caused the resurgence of the disease in Edinburgh, Stirling and Perth.

The disappearance of plague in Scotland coincided with the nadir of the LIA (1650-1700 AD). At such a time, climatic conditions were not so bad as to eradicate rats and fleas, but they may have discouraged the already-diminishing number of rats. Climate aided the eradication of plague, but it was not the limiting factor. Factors will surely have varied in importance from one phase to another. Improvements in both sanitation and ports' quarantine measures may well have had significant roles at this time (Hamilton 1981).

Although plague persisted in eastern Scotland until 1648, it hardly affected the western and northern areas (See Fig. 4.1). Thus, plague occurred in the warmer and drier east. Figures 4.2 and 4.3 are temperature and precipitation graphs for Edinburgh and Tiree. Hamilton (1981) invoked dispersed population and difficulty of travel, to explain the spatial distribution of plague, but he excluded climatic factors. Climate's influence on plague was implied by Sir Robert Gordon who wrote: 'Ther is not a ratt in Sutherland; and if they doe come thither in ships, they die presently how soon they doe smell the air of that Country'. That is, Sutherland, which is in the far north, was too cold to maintain rat populations.

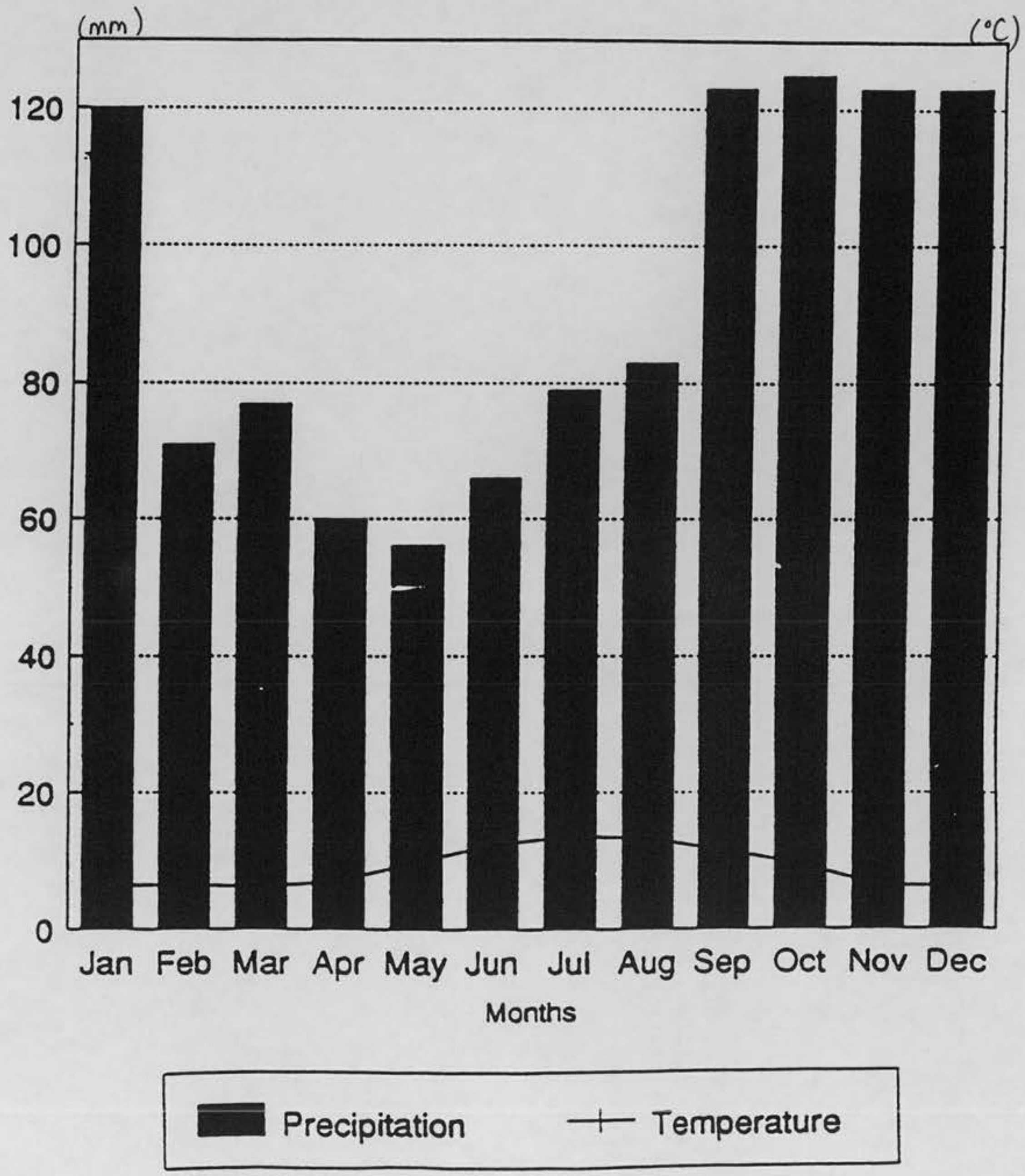
The examination of the plague-climate relationship in the Highlands and west, is shown in Tables 4.5 and 4.6. Nairn, at an altitude of 100m a.s.l., experienced temperatures warm enough (i.e. temperatures above $10^{\circ}C$) for rats to survive from June to October, in 1350-1400 AD. Tiree, however, could only have supported rat populations from July to October. In 1350-1400 AD, both Nairn's and Tiree's July and August temperatures would have allowed fleas to hatch; however, the following cool months would have determined a long maturation period. Thus, few fleas would have developed. In the LIA period, rats could have survived only from June to August in Nairn and from July to October in Tiree. Temperatures never reached 12.8° Cin Nairn. This implies that fleas could not hatch, mature and

Fig. 4.2 Mean Monthly Temperature and Precipitation for Edinburgh (1951-80)



Source: The Meteorological Office (1989)

Fig. 4.3 Mean Monthly Temperature and Precipitation for Tiree (1951-80)



Source: The Meteorological Office (1989)

Table 4.5 The Temperature in the Highlands 1350-1400 AD and 1550-1650 AD

Nairn 1951-80	Edinburgh 1951-80	Difference 1951-80	1350-1400 AD 100 m a.s.l.	1550-1600 AD 100 m a.s.l.
J 2.9	3.3	- 0.4	1.2	0.6
F 3.8	3.5	+ 0.3	2.8	2.1
M 4.9	5.2	- 0.3	3.3	2.7
A 6.8	7.4	- 0.6	5.6	5.0
M 9.6	10.2	- 0.6	8.5	7.9
J 12.5	13.3	- 0.8	11.7	11.2
J 13.6	14.7	- 1.1	13.0	12.4
A 13.7	14.5	- 0.8	12.9	12.3
S 11.9	12.7	- 0.8	10.5	9.9
O 9.9	9.9	0	7.5	6.9
N 5.4	5.8	- 0.4	3.5	2.9
D 3.9	4.3	- 0.4	1.0	0.4

Table 4.6 The Temperature in the West 1350-1400 AD and 1550-1600 AD

Tiree 1951-80	Edinburgh 1951-80	Difference 1951-80	1350-1400 AD	1550-1650 AD
J 6.3	3.3	+ 3.0	5.8	5.2
F 6.4	3.5	+ 2.9	6.5	5.9
M 6.1	5.2	+ 0.9	5.7	5.1
A 7.0	7.4	- 0.4	7.0	6.4
M 9.7	10.2	- 0.5	9.8	9.2
J 12.3	13.3	- 1.0	12.7	12.1
J 13.5	14.7	- 1.2	14.1	13.5
A 13.2	14.5	- 1.3	13.6	13.0
S 11.5	12.7	- 1.2	11.3	10.7
O 9.4	9.9	- 0.5	8.2	7.6
N 6.4	5.8	+ 0.6	5.7	5.1
D 6.2	4.3	+ 1.9	4.5	3.9

spread disease. In Tiree, fleas could have hatched in July and August, but the ensuing cool temperatures would have prevented maturation. In summary, temperatures were too cool to support rat populations for any length of time and too cool to allow fleas to mature.

In addition to the cold, both the north and west experience high humidity and precipiation. Figures 4.2 and 4.3 compare the precipitation for Tiree with Edinburgh. Otten (1932) showed that excessive high humidity is adverse to plague. X.cheopis cannot breed in really damp environments. Therefore, in the north and west, the combination of cold and extreme wetness could have prevented the spread of plague. This is not to suggest that climate alone limited plague in the north and west. The dispersed population and the difficulty of travel in these areas would also have limited the spread of the disease (Hamilton 1981). Also, the relative infrequency of direct maritime contacts between the west and continental ports, is likely to have been a major influence in keeping this area relatively free from plague.

SUMMARY

This section demonstrates the importance of long-term climate in influencing the spread and persistence of plague in Scotland. It is important to address climate's role, because the control of an infectious disease requires an understanding of the causative agent, the vector, the host and the environment in which transmission occurs (Daur 1991). It is not suggested that climate alone caused or prevented the spread of plague; it was merely one factor.

In evaluating the chief climate-plague findings of the work, it is important to keep in mind the limitations of the documentary sources. This work, founded on the available sources however imperfect, reaches the following conclusions. First, Scotland's climate prior to 1349 was not too cool to discourage rats which spread the plague; but in fact was too warm and dry for the fleas which spread the disease. Second, cargo ships in the Little Ice Age carried plague rats into sea and river ports; cold temperatures prevented the spread of rats and fleas and hence, plague into neighbouring areas. Third, cool temperatures and excessive humidity helped to stop plague from spreading to the north and west of Scotland.

THE POSSIBLE INFLUENCE OF CLIMATE ON HISTORICAL OUTBREAKS OF MALARIA IN SCOTLAND

Malaria, one of the most debilitating diseases to afflict humankind, 'has over the millenia accounted for innumerable deaths and shaped the course of human history in regions far beyond its present geographic distribution' (Dobson 1989). Malaria, described as seasonal fevers, ague, marsh fevers, tertian fevers, quartan fevers and intermittent fevers, once prevailed in the marshy areas of south-east Scotland (Flinn et al. 1977) and in the coastal and estuarine marshes of England (Dobson 1989).

The Scottish and English people attributed the 'fevers' to effluvia, arising from places where the ground was excessively wet or marshy (Webster et al. 1986). Today, however, disease is seen as a product of the interaction of the causative agent, the vector, the host and the environment in which transmission occurs (Brandford 1977). In the case of malaria, the agent is Plasmodium. Four species of this parasite cause infection in humans; P.vivax, P.falciparum, P.malariae and P.ovale cause vivax, falciparum, quartan and ovale malaria, respectively (Bruce-Chwatt 1985). In Britain, vivax malaria was most prevalent (MacArthur 1951).

The vector is the Anopheles mosquito, five species of which exist in Britain: A.atroparvus, A.messease, A. claviger, A.plumbeus and A.algeriensis (Cranston et al. 1987). A.atroparvus is thought to have been responsible for malaria in Britain (Dobson 1989). The anopheline mosquito not only serves as the vector, but also serves as the definitive host; humans serve as the intermediate host (Kumar et al. 1987).

The relationship between the disease agent and disease host is well understood. Humans are infected following the bite of an infected female anopheline mosquito. The parasite, which multiplies in the human liver, eventually ruptures the liver cells and invades red blood cells (RBCs). In the RBCs, the parasite ruptures the cells when developed and is released into the circulation. This rupturing occurs every 48-72 hours in vivax malaria. The individual becomes infective 12-17 days after innoculation. However, this period may be prolonged to 8-9 months (Kumar et al. 1987). After infected blood is ingested by a mosquito, it becomes infective 9-20 days later; the infective parasites are then injected into humans on the next occasion (Miller et al. 1990).

The role of environmental factors is less understood than the disease agent and the disease host. Close proximity to marshes (Dobson 1989), the natural habitat of A.atroparvus, is virtually the only environmental variable used to explain the spread of malaria in Britain.

However, various environmental factors have been proposed to explain the eradication of malaria in Britain. These include (1) the drainage and reclamation of swamp land, which would have led to a reduction of the vector population; (2) the introduction of root crops and pasturing by rotation, which would have led to an increase in production of fodder and the number of stabled animals. This, in turn, would have led to a transfer of vectors from humans to animals (Mollineaux 1988) and (3) improved housing which would have eliminated the mosquito's preferred resting places in dark damp corners. This would have led to a reduction in mosquito density (Mac Arthur 1951). Improvements in health and standards of living may also have been critical factors in explaining the diminished severity of malaria (Dobson 1989).

MALARIA AND CLIMATE

Historians and scientists have favoured socio-economic explanations to the virtual exclusion of climatic factors. There are, however, a few notable exceptions. Dobson (1989) notes that 'there was a very close correspondence between fluctuations in summer temperatures and the level of mortality in the autumn and following spring'. Lamb (1977) suggested that 'the chilly summers after A.D. 1690 seem to have eliminated the disease in northern Europe for a time, but it was present again in the warmer years in the eighteenth and nineteenth centuries'.

Climate exerts a powerful influence on the spread of malaria. Gill (1938) stated that 'there can be few, if any,...whose clinical and more particularly whose epidemiological features vary so markedly with climate, as malaria'. Seasonal changes in temperature, rainfall and humidity all have an obvious effect on anopheline mosquitoes (Bruce-Chwatt 1985).

At temperatures above 23°C, egg-laying is completed within 48 hours; below 23° C, the cycle is completed within 72 hours. Rising temperature tends to increase the growth rate of mosquito populations from egg to adult: at 31°C, 7 days are necessary to complete this transformation; at 20°C, 20 days are needed. The optimal temperature range for Anopheles is between 20-30°C; above 30°C, mosquitos begin to die more quickly. When temperature exceeds 35°C, the longevity of Anopheles is drastically reduced and this has a direct bearing on transmission potential. If mean daily mortality is 35% or greater, less than 1% will survive the necessary time for the development of Plasmodium to the infective stage (Bruce-Chwatt 1985). The minimum temperature permitting the development of the parasite, P.vivax, is 15°C (Mollineaux 1988). It takes 16 days for the mosquito to become infective at 20°C.

Humidity, as well as temperature, affects anophelines. When humidity is less than 50%, the longevity of Anopheles is 'drastically reduced' (Bruce-Chwatt 1985). Preferred humidity is 60% or more (Mollineaux 1988). The best conditions for development of Plasmodium in Anopheles and transmission of the infection are when: (1) relative humidity is at least 60% and (2) mean temperature is between 20-30°C (Bruce-Chwatt 1985).

Precipitation, by providing the medium for the aquatic stages of the anopheline life cycle, obviously has a fundamental role to play in mosquito production. Rainfall also serves to increase atmospheric humidity (Graham 1988), increasing the longevity of the mosquito. Lastly, strong winds probably affect flight and prevent egglaying. However winds may extend their flight ranges (Bruce-Chwatt 1985).

In the light of the lack of study of the climatic influence on the spread of malaria, this section demonstrates that: (1) Scotland's average temperatures from the Medieval Warm Epoch through to the Little Ice Age were suitable for the spread of malaria; (2) malaria outbreaks coincided with wet summers; (3) precipitation was insufficient in the Medieval Warm Epoch to provide the necessary aquatic habitat for the mosquito and (4) high summer temperatures of over 15°C are linked to malaria outbreaks in the subsequent years.

METHOD

The overall approach used in this section is first to establish the timing of outbreaks of malaria and then to look for relationships between these and periods of warm and cold climate. Particular attention is paid to the Medieval Warm Epoch (1150-1300 AD) and the Little Ice Age (1550-1700 AD), since this is when climate change is most marked.

It is difficult to determine the dates of outbreaks of malaria. One reason is the problem of determining the aetiology of various fevers, described in the writings of physicians of the 17th and 18th centuries (Bruce-Chwatt 1988). This is because: (1) it is impossible to be certain of equivalents in modern medical terminology (Flinn et al. 1977); (2) it can never be known if the disease was described in fanciful terms (Bruce-Chwatt et al. 1980); (3) a plethora of names or phrases was applied inconsistently to the afflictions and (4) the term 'ague' was frequently employed to characterize any acute febrile illness (Webster et al. 1986). Because of these problems, there is much disagreement among the medical profession and historians over what was a malaria outbreak. For example, Creighton (1891-94) believed that neither the epidemic agues of the Restoration period nor those of the 16th century were malaria; while others think that they were (Bruce-Chwatt et al. 1980). Because of these problems, few studies have examined the true extent and impact of malaria (Bruce-Chwatt 1976; Bruce-Chwatt 1977; Bayliss 1985 and Bruce-Chwatt et al. 1980). Dobson (1989) has undertaken a large historical survey of patterns of disease in England. No such history of malaria has yet been published for Scotland.

In order to determine if temperature checked the spread of malaria, the effects of the average temperatures during the cool period of the Little Ice Age were investigated in relation to (1) the mosquito, (2) the development of Plasmodia in anophelines and (3) the transmission of infection. In order to investigate the role of high temperatures, the number of days with maximum temperature over 30°C was determined for the Medieval Warm Epoch and linked to the disease.

The principal data base used is the mean monthly temperature record for Edinburgh (800-1900 AD) (See Chapter Two). Maximum daily temperatures were estimated by inspection of recent records, for years when the mean summer temperatures were the same as the historical periods in question. Maximum daily temperatures in Edinburgh in the years 1961-80 were used as the analogy for the Little Ice Age. There is no temperature analogy for the Medieval Warm Epoch in Edinburgh. Therefore, the record from Kew for the years 1881-1980 was used, because the mean summer temperatures at this time were identical to the mean summer temperatures in Edinburgh in the Medieval Warm Epoch. This record will over-estimate temperatures in Edinburgh, as maximum temperatures in Scotland are a few degrees less than in England (The Meteorological Office 1989). This, however, is unimportant because if malaria infection could survive the warmer Kew temperatures, it could certainly survive the temperatures in Edinburgh.

To find the relationship between malaria outbreaks and precipitation, malaria years were checked against Lamb's (1977) summer wetness/dryness indices and calculated precipitation. Because of the sparseness of malaria outbreaks in Scotland, the data base was widened by incorporating outbreaks in England.

Finally, summer temperatures were examined in order to determine if high summer temperatures, in part, predicted malaria outbreaks in the following year. Manley's (1974) central England temperature record was graphed with both Scottish and English outbreaks of the disease, because Mossman's (1896) Edinburgh temperature record only extends back to 1764. This is unimportant as Manley (1953) stated, '...even the short-term anomalies of temperature found in his English midland data are also available in Mossman's series for Edinburgh'. It is important to remember, however, that Edinburgh was, on average, 0.8°C cooler than central England (Duncan 1991).

RESULTS

Table 4.7 shows the number of days with maximum daily temperature above 15°C, the minimum requirement for development of P.vivax, during the Little Ice Age; as well as the number of days with maximum daily temperature between 20-30°C, the optimal range for anopheline mosquitoes and the transmission of disease. Table 4.8

Table 4.7

The Little Ice Age in Edinburgh and South-East Scotland

Number of Days with Maximum Daily Temperature above 15°C	Number of Days With Maximum Daily Temperature Between 20-30C
88	13

Source: The Meteorological Office (1982).

Table 4.8

The Medieval Warm Epoch

Number of Days Over 30°C
3

Source: The Meteorological Office (1984).

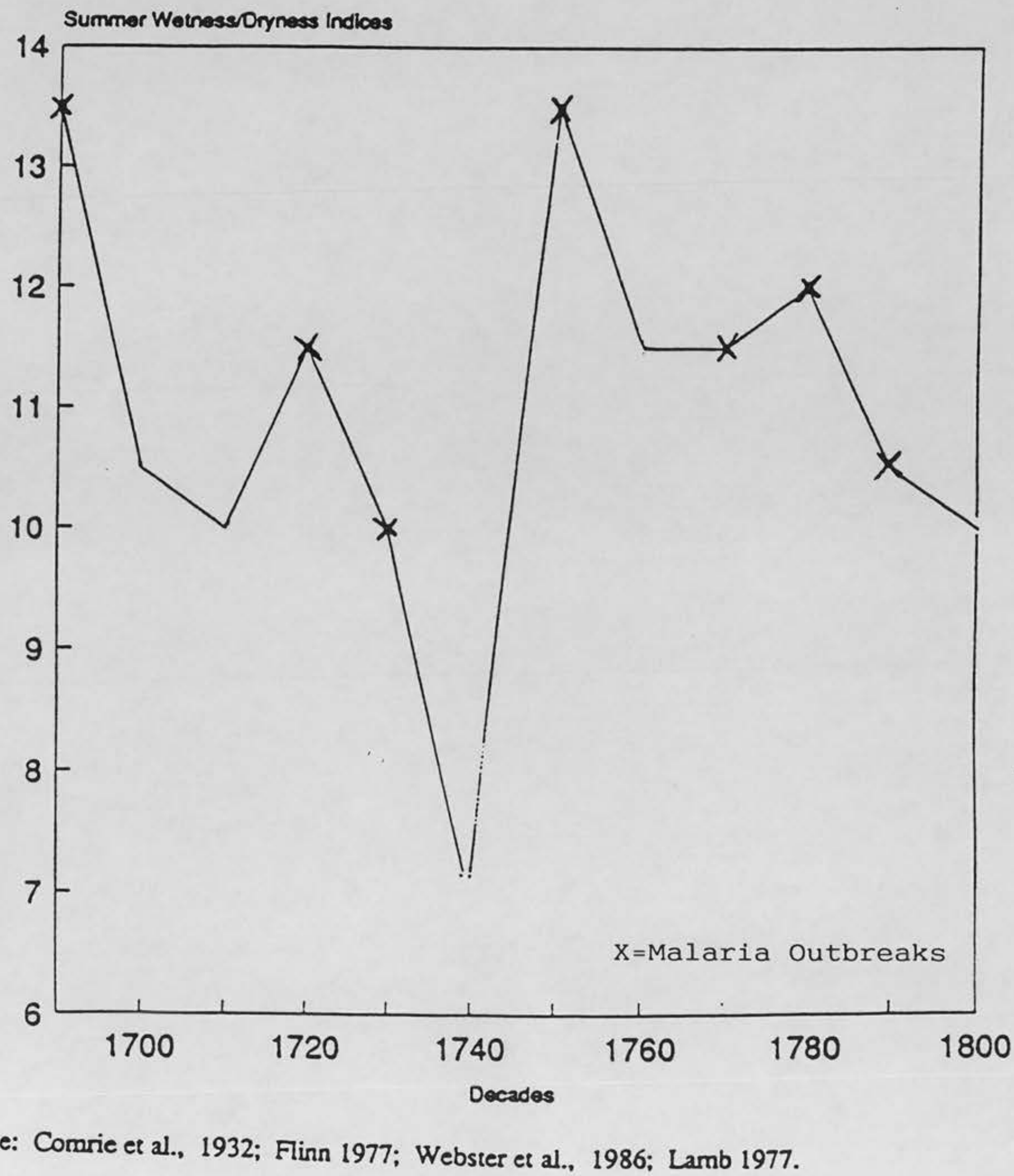
shows the number of days with maximum temperature over 30°C for Kew 1881-1980, which is the analogy for the Medieval Warm Epoch. Figure 4.4 graphs Lamb's summer wetness/ dryness indices and malaria outbreaks in Scotland for the 18th century. Figure 4.5 graphs Lamb's (1977) summer wetness/dryness indices and malaria outbreaks in England, from the 16th-19th century. Figure 4.6 graphs Lamb's (1977) calculated rainfall (in percentages) for 800-1900 AD and malaria outbreaks in England. Figure 4.7 shows the correlation between malaria outbreaks and central England mean summer temperature.

DISCUSSION

In order to determine whether temperature checked the spread of malaria, the effects of the average temperatures during the cool period of the Little Ice Age and the warm period of the Medieval Warm Epoch were investigated in relation to (1) the mosquito, (2) the development of Plasmodia in anophelines and (3) the transmission of infection.

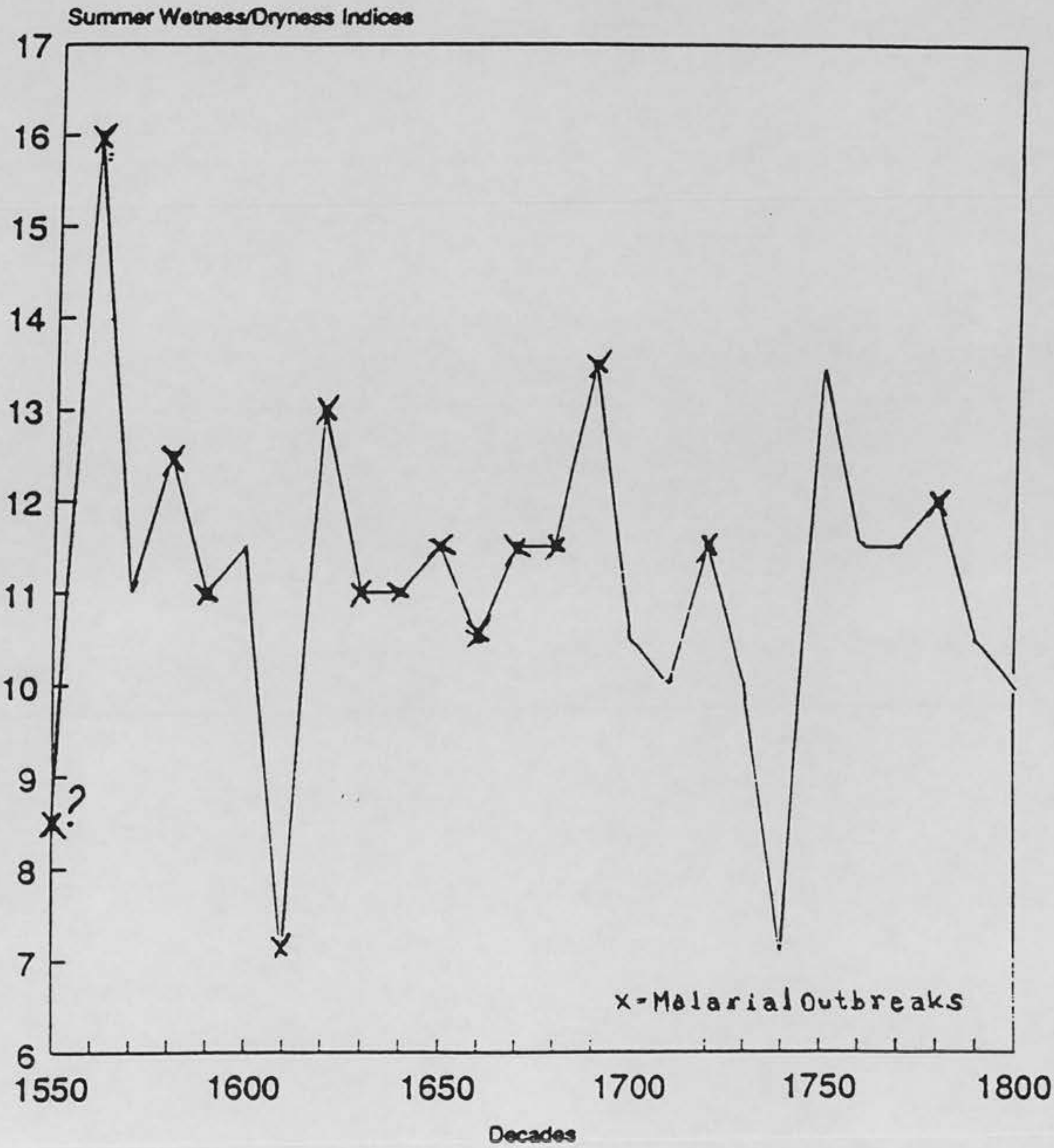
From Table 4.7 the following is apparent. In summer, (June, July and August) of the Little Ice Age, there were 81 days with maximum temperatures greater than 15°C; during this time P.vivax could have developed in the mosquito vector. There were 44 days with temperatures greater than 20°C, representing optimal temperatures for transmission. This figure over-estimates the actual number of days, because it is derived from the 18.0-20.9°C temperature category.

Fig. 4.4 Years of Malaria Outbreak in Scotland and Lamb's Summer Wetness/Dryness Indices



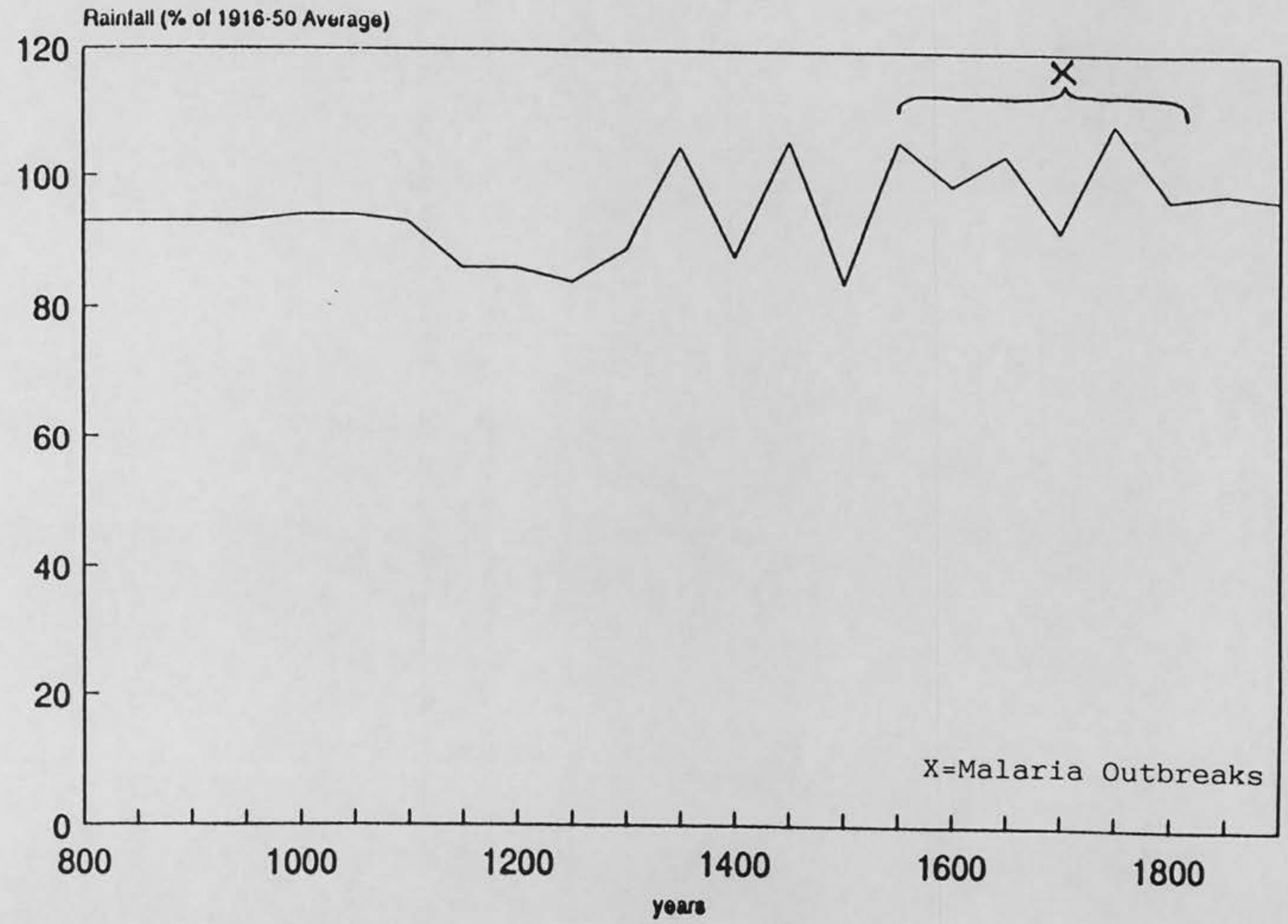
Source: Comrie et al., 1932; Flinn 1977; Webster et al., 1986; Lamb 1977.

Fig. 4.5 Years of Malaria Outbreak in England and Lamb's Summer Wetness/Dryness Indices



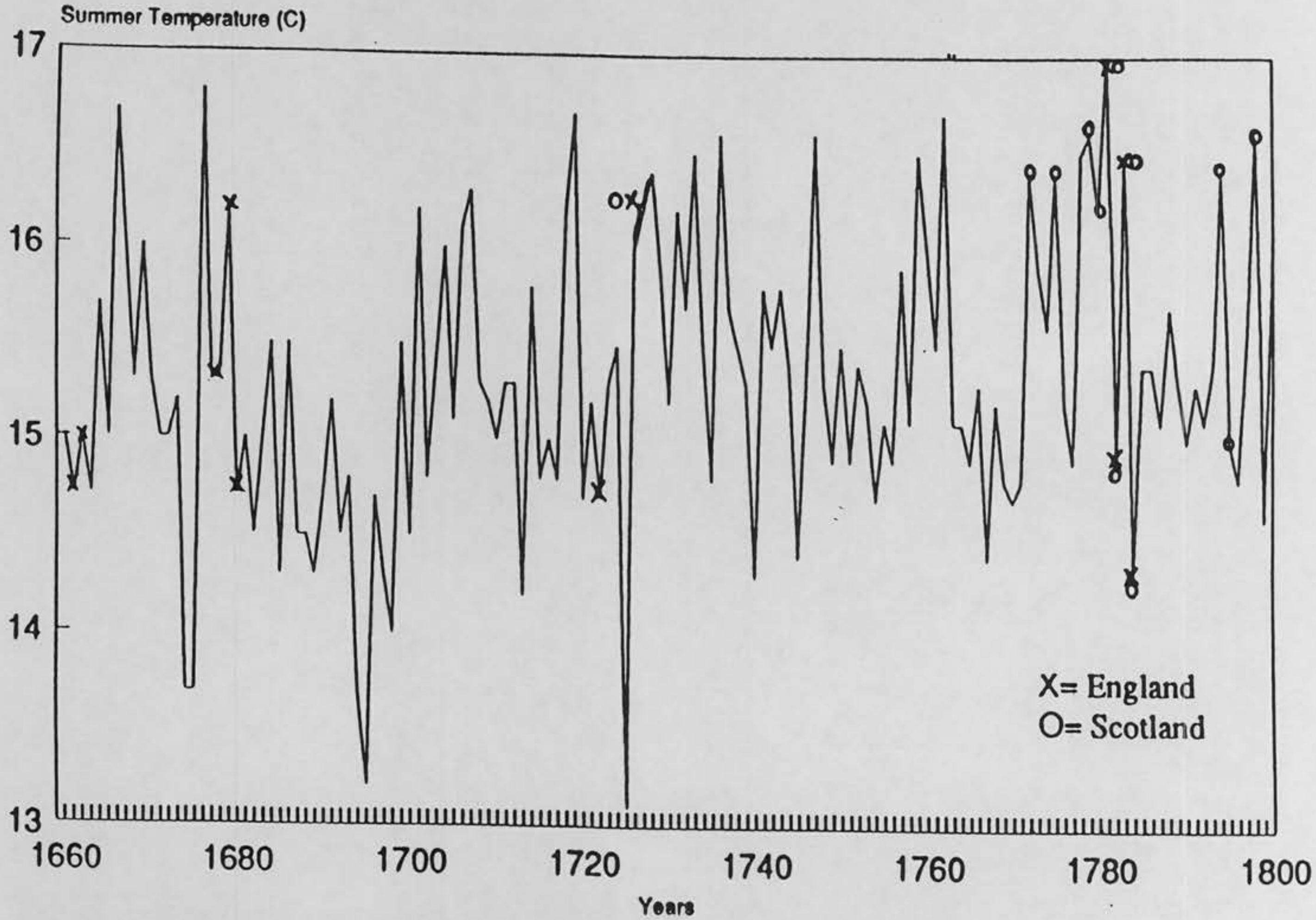
Source: Creighton et al., 1891-94; Bruce-Chuatt et al., 1980; Bruce-Chuatt 1988; Lamb 1977.

Fig. 4.6 High Summer (JA) Rainfalls and Years of Malaria Outbreak



Source: Creighton et al., 1891-94; Comrie et al., 1932; Lamb 1977, Flinn 177; Bruce-Chuatt et al., 1980; Bruce Chuatt 1988.

Fig. 4.7 Mean Summer Temperature in Central England and Years of Malaria Outbreak



Source: Creighton et al., 1891-94; Comrie et al., 1932; Manley 1974, Flinn 177; Bruce-Chuatt et al., 1980; Bruce Chuatt 1988.

It is interesting to carry out some simple calculations to illustrate the impact of changing climate on mosquito life cycles. Taking the coldest period, the Little Ice Age, it seems malaria could have occurred. Anophelines lay their first eggs 4-5 days after emergence; prior to laying this first batch, the mosquitos feed 1-2 times (Bruce-Chwatt 1985). In subsequent cycles, a batch of eggs is produced after each feeding. As mentioned earlier, the length of this cycle depends on air temperature; at 23°C, it takes 48 hours and below this temperature, it takes 72 hours.

If a mosquito ingested Plasmodium on the first feed, the insect would be infective by day 17. There were 13 days with temperatures greater than 23°C and during this period a mosquito could have fed every third day. For these years, Edinburgh, with a mean annual temperature of 8.7°C, os 0.5°C warmer annually than Nairn, with an average annual temperature of 8.2°C (The Meteorological Office 1989). On average, summer daily temperatures were less than 23°C, and thus it is more likely that a mosquito would have fed every fourth day. Theoretically, the mosquito could have have passed on the infection to humans on the 17th, 21st and 25th day of life. However, not all feeds are likely to have been on man, since A.atroparvus also feeds on animals.

The implication is that the average temperatures in the Little Ice Age were not so cool as to prevent the spread of malaria, since insects could have survived to pass on the infection. This hypothesis may be supported by Flinn et al. (1977) suggestion that malaria may have been present in Scotland during the 1690s, the nadir of the Little Ice Age (Figure 4.4).

At the other extreme, one can examine the climate of the Medieval Warm Epoch to see the effect of warmth. Since temperatures of 30°C or more only occur on 3 days of the year (Table 4.8), summer temperatures were not too warm as to check malaria transmission. In fact, the warmer temperatures were likely to have been more conducive to the vector, the agent and transmission of the disease. The longevity of the mosquito is likely to have been increased (Bruce-Chwatt 1985). P.vivax could have developed in the vector for over 88 days. As temperatures of 23°C were reached on 16 days; then, insects could have fed every 3rd night, thus increasing the rate of transmission. Again, it is not suggested that there were sixteen consecutive days with temperature greater than 23°C. It is likely however, that there were short runs of high temperature. During these runs of high temperature, a mosquito could have fed every third day. In summation, it appears that neither the average summer temperatures of the Medieval Warm Epoch nor of the Little Ice Age would have checked the spread of malaria.

From Figures 4.4 and 4.5, it is apparent that malaria outbreaks coincided with summers of high precipitation. From seven decades with outbreaks in Scotland, the average summer wetness/dryness index is 11.7. From 14 decades with outbreaks in England, the average is 11.5. There is, however, one extreme outlier, the 1610-19 decade. This is to be expected, as a lack of precipitation would have 'drastically reduced' the aquatic habitat of the anopheline, which in turn, would have reduced the number of adult mosquitos (Bruce-Chwatt 1985). The occurrence of malaria in the dry decade of 1610-19 may be explained by the following. Although the decade was very dry, the years of 1612 and 1613, in which the epidememic occurred, may actually have been wet.

Figure 4.6 shows that it was much drier during the Medieval Warm Epoch, which had 18% less precipitation than the Little Ice Age. Malaria outbreaks were unknown during the Medieval Warm Epoch, but they were common throughout the Little Ice Age in England. In light of this, it is suggested that malaria was suppressed in the Medieval Warm Epoch, at least partly, because of reduced precipitation. Decreased rainfall is likely to have reduced the aquatic habitat of the mosquito, which in turn would have led to a reduction in the density of the vector population (Rafatjah 1988). Reduced precipitation is unlikely to have altered humidity significantly, since humidity in Edinburgh is mostly determined by proximity to the sea, rather than by rainfall (The Meteorological Office pers.comm. 1992). Therefore, longevity of the mosquito population, which depends on humidity, is unlikely to have been significantly altered in the Medieval Warm Epoch.

Figure 4.7 shows that malaria outbreaks tend to follow hot summers and epidemic malaria often carries over into the next year, despite considerable decreases in temperature. This is because victims often relapse 28-40 weeks after the initial attack; these are the spring relapses. Therefore, Dobson's (1989) assertion that there was a close correspondence between the hottest summers and mortality in the following spring is supported. There is also inverse supporting evidence in that Lamb (1977) suggested that the chilly summers after 1690 AD seemed to have eliminated the disease from northern Europe for a time; indeed, malaria did not reappear in Scotland or England until the 1720s.

SUMMARY

This section demonstrates the apparent relationship of malaria outbreaks with particular long-term, medium-term and short-term climatic conditions. Climate plays a role because it influences the life cycle of both the vector and the host, as well as the environment in which transmission occurs. However, it is worth adding two points, reflecting limitations of this study. In the first place, climate is only one of several environmental and socio-economic factors which will influence the spread of malaria. In the second place, the documentary evidence of malaria outbreaks is likely to be incomplete or in some cases ambiguous.

Bearing in mind these limitations, there are grounds for identifying the following relationships between climate and malaria. First, neither the average temperatures of the Medieval Warm Epoch nor of the Little Ice Age appear to have been limiting to the spread of malaria; in fact, the warm temperatures of the Medieval Warm Epoch were likely to have helped the development of malaria. Second, malaria outbreaks seem to coincide with summers of high precipitation. This is because increased rainfall is necessary to maintain the aquatic habitat of the mosquito. Third, reduced precipitation during the Medieval Warm Epoch may have limited malaria at a time when temperature conditions were favourable. Fourth, malaria outbreaks seem to follow warm summers. In combination, the optimum climatic conditions for outbreaks of malaria in Britain, occur when there are high summer temperatures in one year, followed by high precipitation in the following year.

Finally, this section investigates the relationship between ergotism, the Scottish witch-hunts and 'difficult weather'.

ERGOTISM, THE SCOTTISH WITCH-HUNTS AND 'DIFFICULT WEATHER'

The third section of this chapter investigates the relationship between ergotism, the Scottish witch-hunts and 'difficult weather'.

'In no country did the witch-cult flourish more rankly, in no country did the belief persist more lately, and in no country did the prosecution of sorcery rage fiercer and the fires blaze brighter than in Scotland' (Summers 1927). During the three great periods of Scottish witchcraft persecutions, 1590-97, 1640-44 and 1660-63, over six thousand individuals were tried and subsequently executed

(Black 1958). Innumerable causal factors including the Reformation and the Counter-Reformation (Summers 1927), the religious zeal of the clergy, the use of judicial torture (Black 1958), the rise of the modern state and the development of capitalism (Midlefort 1972), the great social and intellectual upheaval of the period (McFarlane 1970) and the hatred of women have all been put forward to account for the mass hysteria and slaughter of the Scottish witch-hunts.

More recently, Caporael (1976) presented a circumstantial case that linked ergotism or ergot alkaloid poisoning and the Salem witch trials of 1692. Ergot is usually caused by the fungus Claviceps purpurea, but can be caused by other fungi oi the genus Claviceps. The fungus grows on 1000 host plants which belong to Gramineae, the grass family. This embraces 620 genera which suppply humans with forage and cereal crops (van Rensburg et al. 1979). Despite this, ergot is most commonly found in rye (Barger 1931; van Rensburg et al. 1979; Marasas et al. 1987). This is because rye, unlike other cereals such as wheat, oats and barley, depends largely on cross-fertilization and thus opens its glumes in order to receive pollen from other plants. This opening greatly increases the risk of infection by ergot (Hayes 1988). Wheat, oats and barley are, therefore, rarely attacked. As a result, the distribution of ergot is very closely associated with rye cultivation (Barger 1931).

Sclerotia of the fungus replace the individual grains of the host plant (Webster 1985). These sclerotia contain a large number of powerful pharmacological agents: the ergot alkaloids (Aellig 1978). If contaminated rye is utilized in the baking of rye-bread, those consuming the loaves might suffer from ergotism (Caporael 1976).

Two types of ergot poisoning may result from the ingestion of contaminated rye: convulsive and gangrenous ergotism. Convulsive ergotism is characterised by the following symptoms: epileptiform convulsions; spasms of the fingers, toes, face, vocal chords, oesophagus and diaphram; violent retching and diarrhoea; ravenous hunger; crawling and tingling sensations underneath the skin; pronounced anaesthesia of the skin; paralysis of the lower limbs; delirium; imbecility and a loss of speech (Aellig 1978). Gangrenous ergotism will not be discussed here, as it was convulsive ergotism which was implicated in the Salem witch trials.

In December of 1691, eight girls were affected with unknown 'distempers'; their behaviour was characterised by disorderly speech, odd postures and convulsive fits. After no explanation could be provided for the illnesses, accusations of witchcraft were made by the girls. Witches were accused of choking, pinching, pricking with pins and biting the afflicted; in fact, the purported actions of the witches were probably the symptoms of the diseased.

In summary, Caporael (1976) presented a circumstantial case which proposed that the physical manifestations of the afflicted girls, which initiated the witch-hunts (in which twenty individuals were executed, two died in prison and one hundred and fifty were imprisoned), resulted from ergotism. Psychological and social factors then gave meaning to the symptoms. Caporael (1976) further postulated that ergotism might be implicated in other witch trials.

As a result of Caporael's work, Parry (1978) speculated about a relationship between the Scottish witch-hunts, 'difficult weather' and ergotism. Moreover Matossian (1989) suggested the significance of the correspondence of witch-persecution and rye-growing areas in Scotland. An appealing case may be made because the development, spread and germination of ergot spores is favoured by cool, wet conditions. These tend to prolong the flowering period of cereals and grasses and so increase the chance of infection (Hayes 1988).

Furthermore, the extent to which infection occurs is largely determined by the weather during the flowering period (The Scottish Agricultural Colleges 1982). In Britain, when the incidence is high, there is an apparent correlation of high relative humidity and low maximum temperature in June (Webster 1985). The Scottish witch-hunts of the 1590's and of the 1640's coincided with the 'especially difficult weather of the periods 1591-98 and 1647-49' (Parry 1978). Both periods were characterized by a run of particularly cool, wet summers - ideal conditions for the development of ergot.

Although the occurrence of outbreaks of ergotism is largely influenced by climatic conditions (Marasas et al. 1987), it is important to stress that other factors also play a role. These include cultivation techniques, harvesting methods, grain selection and storage conditions (Hayes 1988).

In light of the above, this section aims to test the hypothesis that ergotism may have played a role in the Scottish witch-hunts. The approach is to establish: (1) if any disease which might correspond to ergotism occurred at the time of the witch-hunts; (2) if rye or wheat were consumed at the time of the three Scottish witchcraft persecutions; and (3) if rye or wheat was imported at the time of the Scottish witch-hunts.

It is difficult to determine the date of outbreaks of past ergotism. One reason is the problem of determining the aetiology of various illness described in the writings of the physicians of the 16th and 17th centuries (Duncan 1992). This is because it is impossible to be certain of equivalents in modern medical terminology (Flinn et al 1977) and it can never be known if the disease was described in fanciful terms. On account of these problems, there is much disagreement over the definition of an ergot outbreak. For example, Creighton et al. (1891-4) believed that the first instance of ergotism in Britain occurred in 1762 in England. Matossian (1989), however, believes that Creighton failed to diagnose most the past ergotism epidemics.

Matossian suggests that the earliest detailed account of ergot was an English physician in 1603. She further suggests, by the middle of the 17th Century, English physicians were making associations betwen diet and central nervous system disorders. Barger (1931) in contrast, suggested that ergotism was hardly known in England, because of its limited distribution, until it was described in 19th Century medical literature.

Bearing in mind the lack of agreement regarding what was an ergot outbreak, there are grounds for suggesting that ergot was not present at the time of the Scottish witch-hunts. Erogtism was known for centuries under a plethora of names in continental Europe, probably because of its extensive distribution in time and space (Table 4.9). In view of the lack of a word for ergot in Scots and an absence of evidence for ergot poisoning in Scotland, it would appear unlikely that ergotism occurred at the time of the Scottish witch-hunts.

However, because the primary sources relevant to health care in 17th century Scotland can never be complete, it is possible that ergotism could have occurred earlier. Therefore, an investigation of Scottish diet was undertaken in order to determine if rye or wheat, the cereals chiefly responsible for ergot poisoning, were consumed at the time of the Scottish witch-hunts. Unfortuately, little information exists on early Scottish diet, but it is possible to examine archaeological and historical sources in an attempt to reconstruct Scottish diet.

Table 4.9

Names for Ergot

German	French	Latin
Rockenmutter	ergot	Calcar
Mutterkorn	argot	Clavus
Kornmutter	ble	Clavus secalinus
Kornmuhme	bled cornu	Clavus siliginis
Roggenmuhme	chambucle	Grana secalis degenerata
Meelmutter	mane	Secalis mater
Mutterlein	ebrun	Orga
Rockenmutterle	bled avorte	Secale cornutum
Mutterkornlein	bled ergote	Secale luxurians
Stiefmutterkorn	bled farouche	Spermoedia clavus
Kornvater	bleds fourchus	Sphacelia segetum
Kornmanner	bled have	
Hasenbrod	bled rachitique	
Krahenkorn	faux seigle	
Rezroggen	seigle cornu	
Rezkorn	seigle corrompu	
Hahnenbrod	seigle a l'eperon	
Martinskorn	seigle ivre	
Wolfzahne	seigle noir	
Kornzaphen		
Hahnensporn	**Italian**	**English**
Horn		
Vogelsporn	grano allogliato	ergot
Bockshorn	grano cornuto	
Durrkorn	grano sprone	
Taubkorn	grano speronato	
der taube Rocken	segala allogliata	
Rankkorn	segala cornuta	
Schwarzkorn	sperone di gallo	
Tollkorn	chioda segalino	
Achterkorn		
Afterkorn		
Brandkorn		
Brandrocken		
Erdenkoph		
Faulkorner		
Hungerkorn		
Klapp		
Kummerkorn		
Mehldrine		
Moderkorn		
Muhldrie		
Mutterzaphen		
Rundrie		
Todtenkoph		
Todtenkorn		

Source: Barger 1931

Archaeological sites provide information on cereal remains. These sites do not necessarily provide a record of diet, because crops may have been grown for purposes other than human consumption. Boyd (1988) presented a catalogue of charred and waterlogged cereal remains from archaeological sites in Scotland. The catalogue which is 'moderately complete up to 1986', lists the following sites: 6 Neolithic; 48 Bronze Age; 22 Iron Age; 8 Roman; 11 Dark Age, Viking and Pictish; 9 Medieval and post-medieval; and 2 of unknown age. The distribution of excavated sites providing botancal evidence is 'uneven and, to a degree, geographically constrained'. Despite this fact, the catalogue is useful to those researching in the field of Scottish environmental archaeology (Boyd 1988).

Boyd (1988) has suggested that rye occurred only as a 'fringe' cereal, possibly having been cultivated on the eastern seaboard, during the medieval period. Archaeological data would, therefore, suggest that rye was not cultivated in Scotland at the time of the witch hunts. Historical sources,in contrast, would suggest that rye was grown in Scotland in the time period concerned; and in some districts, the crop was grown extensively (Green 1936). Wheat, on the other hand, appears to have been grown in the medieval and post medieval periods (Boyd 1988).

Because the archaeological evidence is sparse and unevenly distributed in space and time, historical third-order sources had to be consulted. These include the Old Statistical Account of Scotland (O.S.A.). Although the

O.S.A. was compiled in the 1790's and the witch trials occurred throughout the 16th and 17th centuries; the O.S.A. is thought to give a fairly accurate picture of Scottish farming life (provided that farm improvements are ignored) as Scottish farming had changed relatively little in the previous six hundred years (Symon 1959). Therefore, the O.S.A. provides glimpses into the diet of the historical Highlanders and Lowlanders.

The Lowlanders subsisted on oats, bere and barley. From the 17th century onwards, all accounts of Lowland diet stress the primacy of oatmeal and ale (Houston et al. 1989; O.S.A. II, III, V, VII, IX and X). Reverend Mr. James Adamson, of Abernyte Parish, reported that the 'staple provision among the labouring class is here, as in almost all of Scotland, oatmeal'. Porridge, brose, sowans and oatcakes were the daily fare; these formed the mainstay of every meal (Symon 1959). Meat was scarcely consumed in the common household (O.S.A. III, V, VII and IX). The Reverend of Orwell Parish reported that 'the poorer sort have oatmeal pottage for their breakfast and supper and broth made of barley for their dinner, this often without flesh'. Bere or barley formed the drink crop (Fenton 1976). An orphan's diet from Hutcheson's Hospital, Glasgow, in 1649, showed that 82% of the nutrients came from oatbread, 5% from meat and 8% from fish. The average diet (based on eight known diets between 1639-1743) included 19.7 ounces of meal and 2.1 pints of ale per day (Houston et al. 1989).

Despite the dependance upon oats and barley in the Lowlands, animal products remained important in the Highlands (O.S.A. XVIII and XX). For example, Breadalbane, in 1594, produced 28 bolls of bere, 710 stones of cheese and 50 stones of butter; thus, only 15% of the caloric intake came from grain (Houston et al. 1989). Martin Martin (1695) reported that the Highlanders subsisted on a diet of butter, cheese, milk and oatmeal.

Bread made from flour was not eaten in Scotland, as wheat was a cash crop for sale and not for home consumption (Fenton 1976; O.S.A. V, VII and X). Parry (1978) has suggested that wheat may have been grown only for rent. Reverand Mr. James Anderson, parish of Abernyte, reported that: 'wheat flower is daily coming more into use' (in the 1790's) and a proprietor in the parish of Longferry reported: 'the consumption of wheaten bread has increased much within these few years'. Peas, on the other hand, were always consumed as a bread crop; it was common to mix bere-meal with about 1/3 pease-meal to produce pease-meal bread (Fenton 1976).

Therefore, neither rye nor wheat, according to written sources, appears to have been consumed in Scotland during the witch hunts. Both crops, however, were extensively cultivated and consumed in England throughout historical times (Franklin 1953).

Although it would appear that neither rye nor wheat was being consumed in Scotland at the time of the Scottish witch-hunts, it is interesting to note that the two crops were imported into Scotland. It has been suggested that nearly every available ship in Scotland must have been diverted to the Baltic for grain, normally rye, in the years 1574-5, 1595-7 and 1622-3 (Lythe 1976). After 1660, rye shipments were 1/20th of what they were in 1600 (Smout 1963). It is important to note, however, that a part of the imported grain was later re-exported. For example, in 1598, despite its being a year of famine, some of the grain passing outward through Edinburgh customs is referred to a 'Danskyn wheat' (Smout 1963). In summary, it is unlikely that contaminated rye may have been responsible for the Scottish witch-hunts because only one of the Scottish witch-hunts began in 1590, whereas the famine did not begin until 1594, and the greater-than-average rye imports did not occur until 1595.

SUMMARY

It is concluded that ergotism is most unlikely to have played a role in the Scottish witch-hunts. This is because there is no documentary evidence of ergot poisoning in Scotland during the witch-hunts. Furthermore, in order to develop ergotism, contaminated rye or wheat must be ingested. Because there is little evidence that rye or wheat was a major part of the diet of the 16th-17th century Scots, ergotism is unlikely to have been responsible for the witch-hunts of that time.

It is possible, however, that other fungal infections might have been involved. Some fungal infections, following ingestion, can cause hallucinations like modern

LSD, often in a very distorted form. The sufferer may perceive others affecting him/her in an evil manner. On the basis of present evidence, the assumption that ergotism was specifically responsible for the Scottish witch-hunts must be considered to be improbable.

CONCLUSIONS

This chapter, like the one before it, aims to assess the influence of climate on humankind. Specifically, this chapter aims to narrow the area of speculation that surrounds the role of climatic change and disease. It does so by focusing sharply upon secular, medium-term and short-term climatic change and their effects on communicable disease at different scales. The new mean monthly temperature record for Edinburgh, for 800-1900 AD, provides sufficient detail to link climatic change with disease. The methods developed here for closely examining the link between climate and plague and climate and malaria should be useful elsewhere.

The chief findings are as follows. The climate prior to the mid-fourteenth century was not too cool to discourage rats; but it may have been too warm and dry for the fleas to survive. In the north and west of Scotland, however, cool temperatures and high humidity may have helped to prevent the spread of the disease. During the Little Ice Age, ships continued to carry plague rats into ports, but low temperatures inhibited the spread of the rats and fleas and hence of plague.

In respect to malaria, Scotland's average temperatures, from the Medieval Warm Epoch through to the Little Ice Age, were suitable for the spread of malaria. Malaria outbreaks coincided with wet summers. Precipitation was insufficient in the Medieval Warm Epoch to provide the necessary aquatic habitat for the mosquito. Finally, high summer temperatures over 15°C are linked to malaria outbreaks in the following year.

Ergotism is unlikely to have played a role in the Scottish witch-hunts. This is because neither rye nor wheat, the cereals chiefly responsible for the disease, was likely a significant part of the diet of the 16th-17th century Scots.

CHAPTER 5: GLOBAL WARMING IN SOUTH-EAST SCOTLAND AND ITS POSSIBLE INFLUENCE ON AGRICULTURE AND DISEASE

INTRODUCTION

One of the possible applications of an improved understanding of the climate of the past, is to predict the likely climatic variation of the future. This chapter provides a model of seasonal changes in climate that would be associated with predicted greenhouse-gas induced warming in south-east Scotland of the order of 1.0°C; the model is derived by an historical analogue approach, using the temperature record established in Chapter Two. The possible effects of this predicted warming on agriculture and communicable disease are then investigated.

GLOBAL WARMING AND ITS EFFECT IN SOUTH-EAST SCOTLAND

Forecasts of the temperature 40 years from now, based on three-dimensional general circulation models (GCMs) and projected increases in greenhouse gases, suggest an increase in temperature ranging from 1.5°C to 4.5°C (Warrick et al. 1989). The Scottish Meteorological Office (1989) assumes that the best estimate is in the range 0.5°C to 1.5°C.

Unfortunately, at regional scales, the GCMs are unable to simulate even the present weather conditions with any reasonable accuracy, let alone future weather (Warrick et al. 1989). Furthermore, the GCMs simulate climate for regions the size of Great Britain. Even the more advanced models being developed use blocks half the size of England.

Weather is assumed to be uniform within these regions. One approach to the prediction of possible greenhouse-gas induced climatic change at a regional level, is to refer to relevant historical analogues.

Assuming a 1.0°C warming induced by greenhouse gases, this section uses analogous historical data to predict: (1) mean monthly temperature in Edinburgh and south-east Scotland; and (2) the variability and the frequency of extreme temperature and precipitation events. It demonstrates that temperature changes do not, in fact, correlate with precipitation fluctuations and thus no prediction of future precipitation can be made.

METHOD

Edinburgh's mean monthly temperature record in 50-year periods for 800-1900 AD was utilized in order to find an historical analogue for the projected warming. As a first step, Mossman's 1764-1896 temperature curve was analysed to see if it was representative of the last millenium. This was achieved by correlating temperature for six decades (1771-1830), two 30-year periods (1764-1793 and 1841-1870) and individual years (1773, 1783, 1785, 1793, 1846, 1854, 1857 and 1868). Assuming Mossman's temperature record is representative of the longer time period, it is then possible to select representative historical analogues for the predicted 1.0°C greenhouse-gas induced warming.

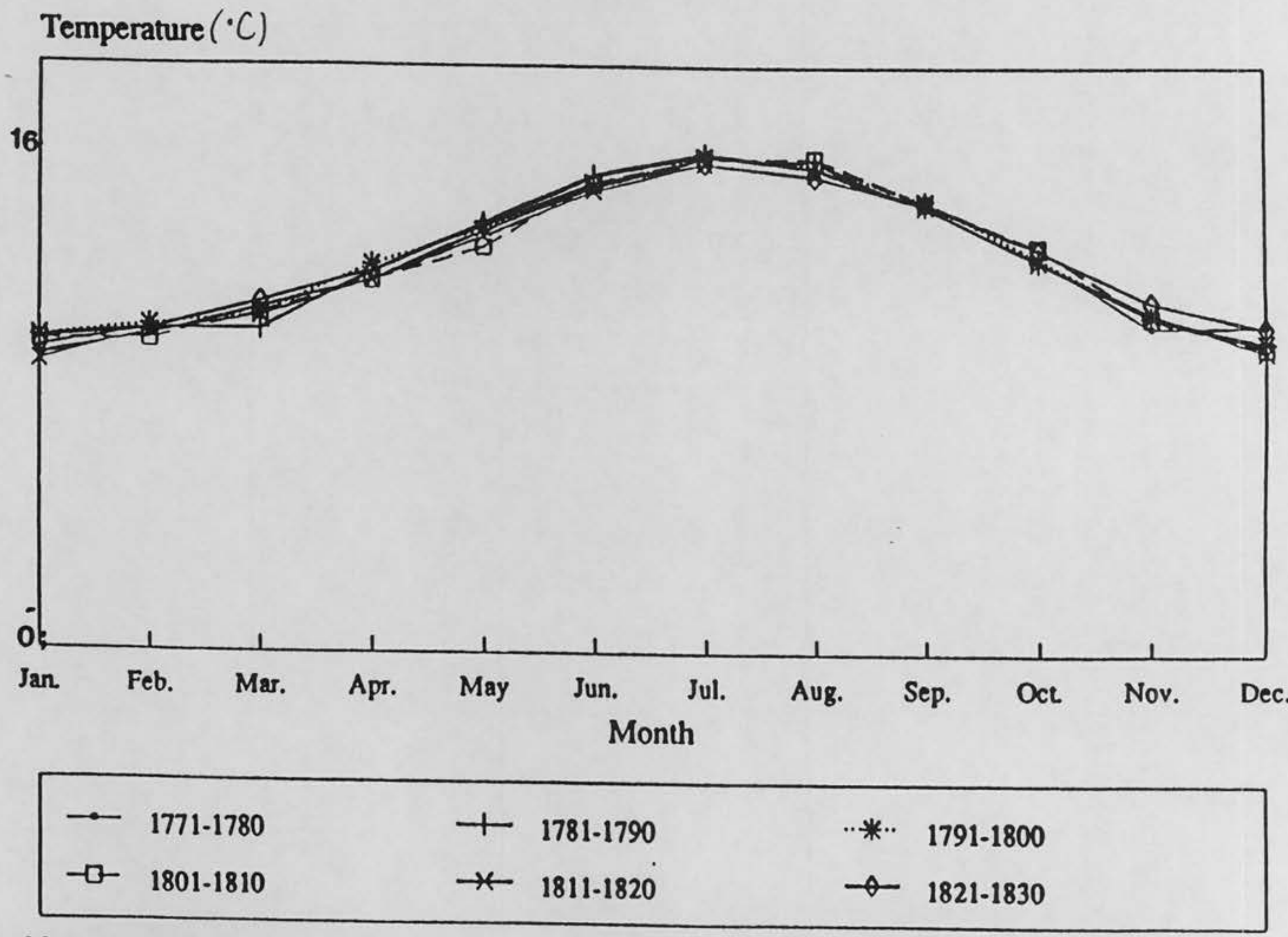
Next, the relationships between (1) temperature and variability in temperature and (2) temperature and variability in precipitation were tested. These were investigated because climatic variability is thought to increase with increasing temperature (Parry et al. 1985). Correlation analyses, relating the mean temperature ($\bar{x}$) and the standard deviation (SD) of both temperature and precipitation, were performed by decade and by 30-year periods.

Last, the effects of small changes in the mean temperature and precipitation are related to the risk of extreme events. These were investigated because the number of extreme events is thought to increase with global warming (Parry et al. 1985). The number of extreme events was compared to the decennial means.

RESULTS

It is important to assess whether the 130 years covered by Mossman's record is representative of the millenium. Tests involved first, the calculation of decennial means and r values. The greatest difference in mean decennial temperature is 0.7°C, over the period 1771-1830; this is a change equivalent to that experienced in the Medieval Warm Epoch (+0.7°C) and that of the Little Ice Age (-0.7 to -0.8°C) (Lamb 1977). Despite this considerable change in temperature, the r values showed almost perfect correlations, ranging from 0.983 to 0.997, suggesting that the seasonal rhythm remains unchanged. Figure 5.1 shows the close correlation between the six decennial mean monthly temperatures for Edinburgh between 1771-1830.

Fig. 5.1 Decennial Mean Monthly Temperature for Edinburgh



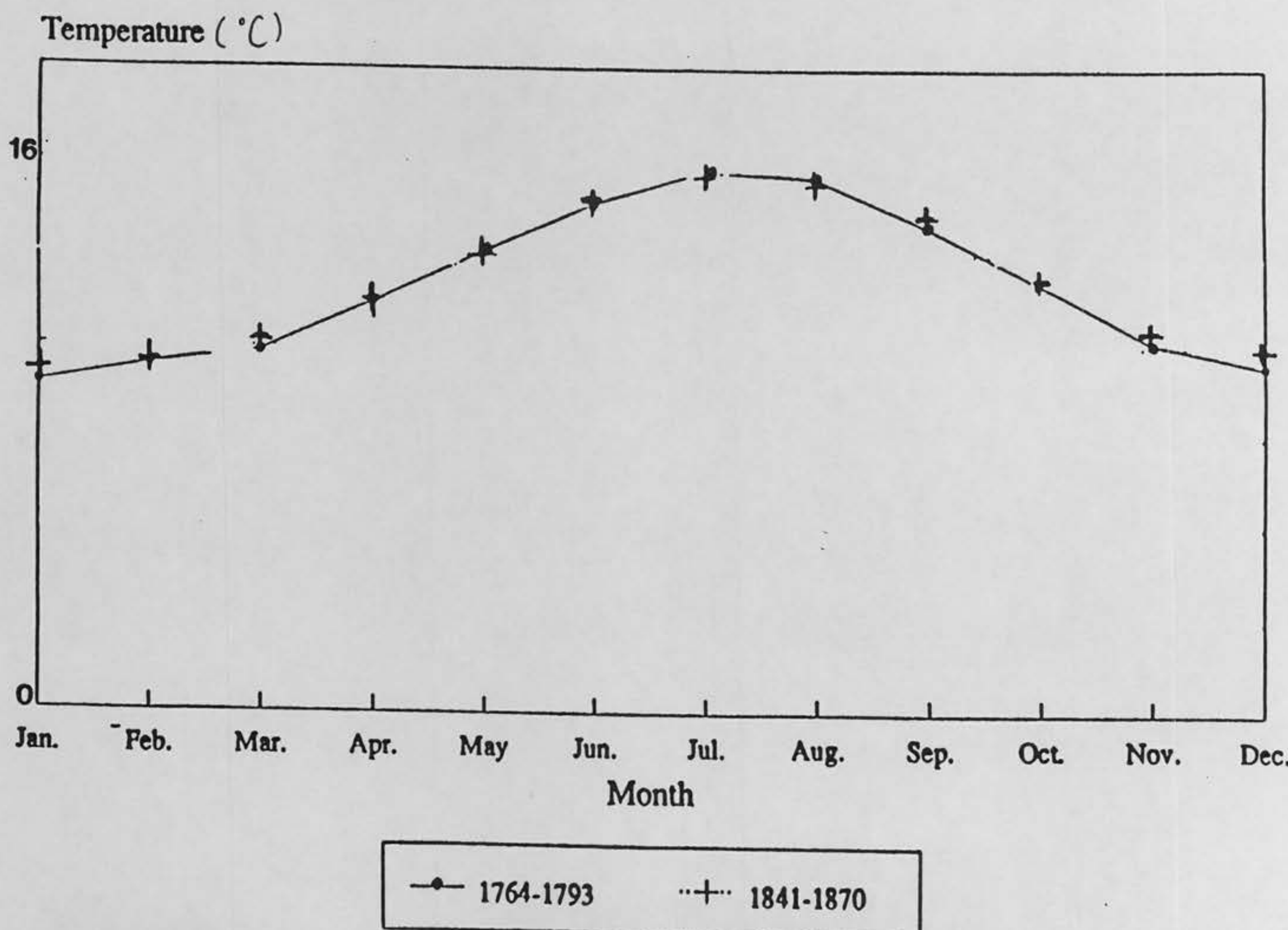
Source: Mossman (1896)

The assumed stability of the seasonal round was further tested by considering the two extreme 30-year periods of 1764-1793 ($\bar{x}$ of 8.17°C) and of 1841-1870 ($\bar{x}$ of 8.38°C). Thirty-year periods were chosen because they are considered to represent an optimum period of time from which to assemble data for a climatic description (The Meteorological Office 1989). The r value was 0.985, which indicates a very high correlation between the two data sets, 1764-93 and 1841-70 (Fig. 5.2). Again, this implies that the seasonal rhythm remains unchanged.

A final test of the stability of the seasonal round involved choosing the four coldest years and the four warmest years, from 1764-1793 and 1841-1870 respectively. The $\bar{x}$ temperatures and r values were calculated for each year. The greatest mean difference in temperature was 2.6°C. Despite the great difference in temperature, the r values remained very high - ranging from 0.848 to 0.970. Figure 5.3 is a graph showing the correlation between the extreme years. There are some obvious outliers, but it is concluded that the seasonal round is stable even during extreme climatic periods.

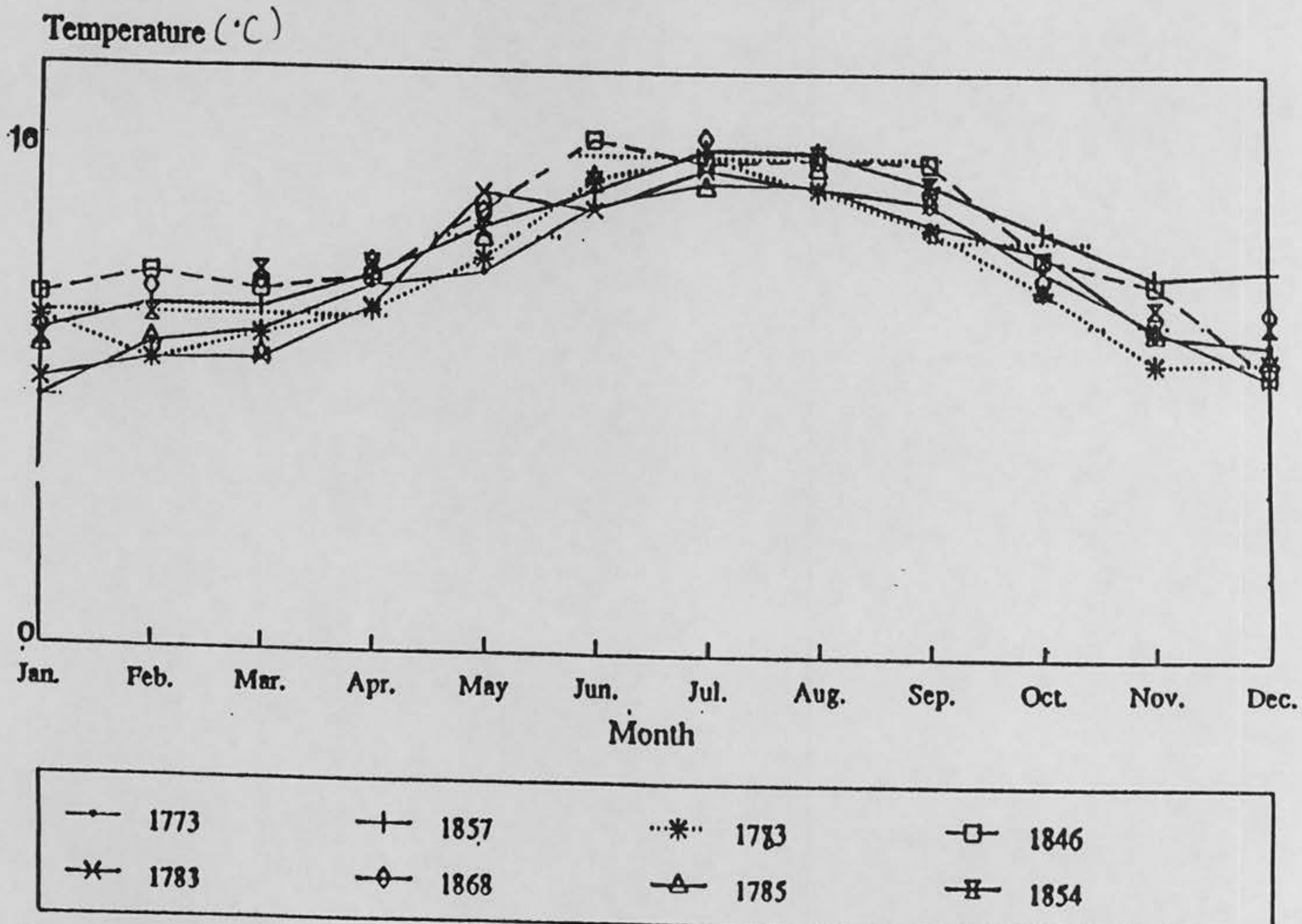
Given that the seasonal round in temperature appears to have remained fairly constant, despite large changes in temperature of as much as 2.6°C, it is reasonable to assume the 130-year period of instrumental monthly temperature is representative of the seasonal variability of the last millenium, which only experienced changes in temperature of 0.7°C above and below normal.

Fig. 5.2 Mean Monthly Temperature for Edinburgh (1764-1793) & (1841-1870)



Source: Mossman (1896)

Fig. 5.3 Mean Monthly Temperature for Edinburgh for Extreme Years



Source: Mossman (1896)

Having established that the 130-year record is representative of the last millenium, an historical analogue for the predicted 1.0° C greenhouse-gas induced warming was chosen. The period, 1900-1950, was assumed to be the 'normal' with an annual mean temperature of 8.6°C. In this case 'normal' refers to average, standard climatic conditions and allows comparison with other climatic periods. This follows the precedent set by Lamb (1977) of using the years 1900-1950 as the 'normal'. The only periods which were close to being a degree C warmer than the normal were: 1150-1200 AD, with a $\bar{x}$ of 9.4°C (an increase of 0.8°C); 1200-1250 AD, with a $\bar{x}$ of 9.3°C (an increase of 0.7°C) and 1250-1300 AD, with a $\bar{x}$ of 9.4°C (an increase of 0.8°C). The period of 1150-1200 AD was taken to be representative of possible future greenhouse warming. The period 1250-1300 AD could just have easily been chosen.

In short, compared with today's temperatures, the predicted warmer period has the following characteristics: (1) winter temperatures increase slightly; (2) summer temperatures increase substantially; and (3) summer mean maximum monthly temperatures increase to 25°C, or more (Chapter Four).

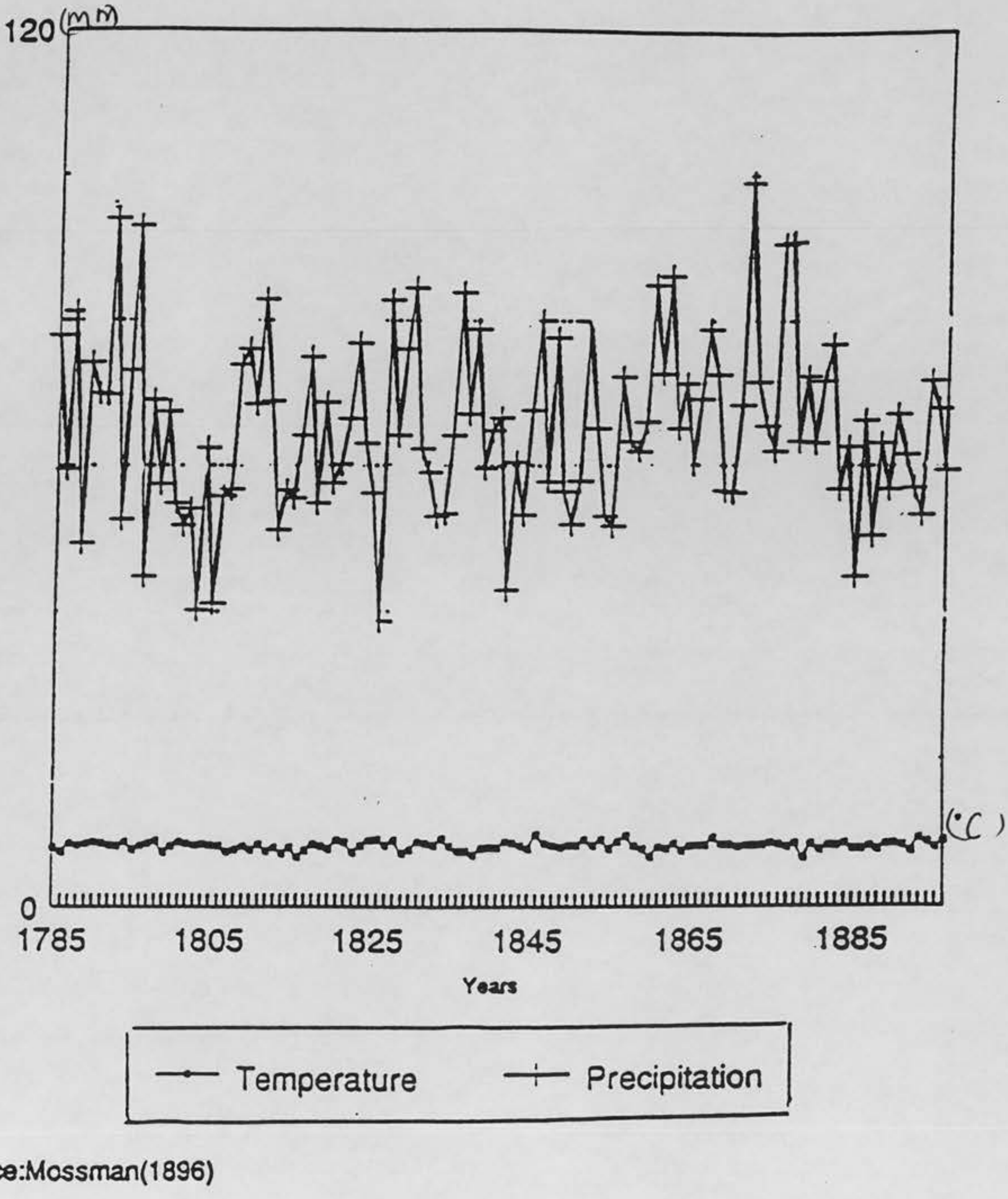
PRECIPITATION

Since temperature changes 'operate closely' with precipitation fluctuations, it has been suggested that greenhouse-gas induced temperature increases are likely to affect precipitation (The Meteorological Office 1989). This assumption was tested for Edinburgh. A comparison was made between Mossman's (1896) annual temperature and precipitation data for 1785-1896 (Chapter Two). Correlation analysis showed that there is virtually no relation annually (r = -0.178) or seasonally. The annual relation is not significant at the p= 0.05 level (.1946 for n=100). The highest r value between temperature and precipitation was found for summer at -0.304 (Fig. 5.4). Although this is significant at the p= 0.05 level (.1946 got n= 00), only 9.24% of the variation is explained. The implication is that with a 0.8^{0}C increase in temperature, there is a possibility that precipitation will decrease slightly during the summer months.

INCREASED VARIABILITY AND FREQUENCY OF EXTREME EVENTS

The relationship between increased temperature and variability of temperature and precipitation was examined because variability is thought to increase with global warming. The relationship between increased annual temperature and the variability of temperature, was investigated by correlation analysis which related the mean temperature and standard deviation of temperature for: (1) each decade from 1771-1890; (2) the two extreme 30-year periods, 1764-1793 and 1841-1870; and (3) the four cold and warm extreme years from the two extreme periods, respectively. In order to determine if the variability of precipitation would increase with increasing temperature, correlation analysis, relating mean temperature and SD of precipitation, was performed for each decade from 1771-1890.

Fig. 5.4 Graph of Mean Annual Temperature and Precipitation for Edinburgh



Source:Mossman(1896)

Extreme events were investigated because they are thought to become more frequent with global warming. First, the decennial means were calculated for 1771-1890. Second, the extreme values were chosen. The choice of extreme values is fairly arbitrary, as temperature is almost normally distributed for Edinburgh. An extreme value was taken to be a value which was greater or less than the mean plus two standard deviations. A high value was required, because the SD for decennial mean temperature was so low; as a result, each temperature became an extreme value. An extreme value for precipitation was taken to be the mean plus one standard deviation. A low value was required because the SD for decennial mean precipitation was high. If a higher value had been chosen, too few extremes would have been found. Third, the number of extreme events was compared to the decennial mean.

Correlation analysis, relating mean temperature and SD of temperature by decade, yielded a r value of -0.393. This result suggests a decrease in variability as the temperature increases. Analysis performed on the SD of temperature for the coldest period of 1764-93 and for the warmest period of 1841-70, gave a r value of -0.748. This suggests that the magnitude of the fluctuations tends to remain fairly constant, despite a considerable change in mean annual temperature. Although the numerical variability remains similar between periods, the direction of the relationship changes. The variability increases in the cool period and decreases in the warm period. Correlation analysis was also performed on the SD of the four extreme cold years and the four extreme warm years; the r value was -0.877. Again, this suggests that the magnitude of the fluctuations remains similar, despite a very great change in mean annual temperature (in this case of 2.6^{0}C) and that variability increases with decreasing temperature.

The r value for decennial mean temperature and SD of precipitation was 0.292, which suggests a very slight increase in variability as temperature increases. However, it is important to remember that annual temperature and precipitation are almost independent variables, the r value being -0.178.

The results of the comparison of decennial mean temperature and precipitation against extreme events, are graphed in Figures 5.5 and 5.6, respectively. There is an increase in extreme events with rising temperature and precipitation. At a temperature of 8.3^{0}C, two extreme values were found; at 8.4^{0}C, six extreme values occurred; at 8.44^{0}C, six extreme values were found for 1850-60 and eight extremes were found for 1820-30. With precipitation of 64.7cm, two extreme values were found and with precipitation of 65.5cm, four extreme values occurred. There appears to be little relation between the number of extreme values and the mean temperature or mean precipitation of decadal averages.

Fig. 5.5 Decennial Mean Temperature and Extreme Temperature Events

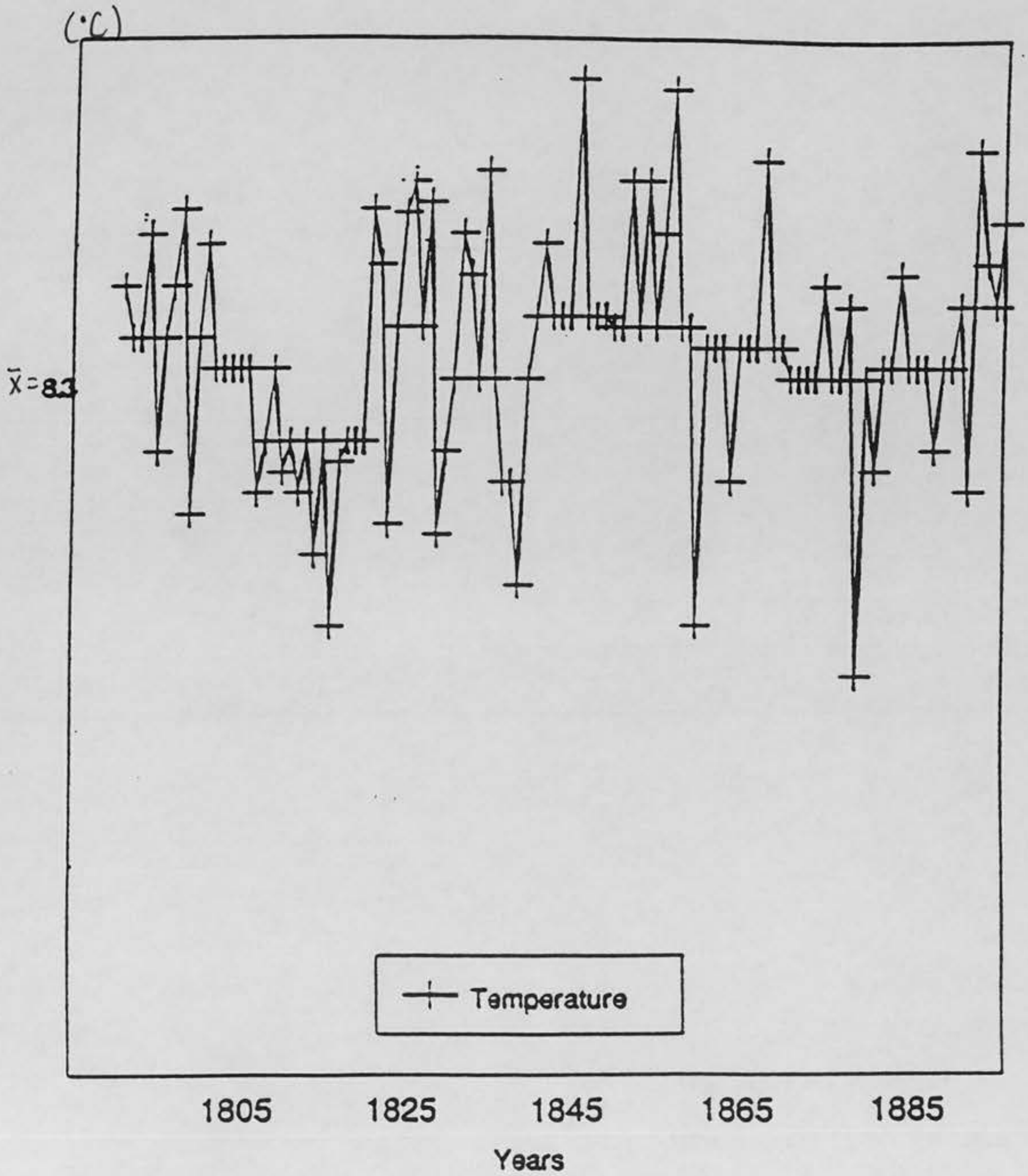
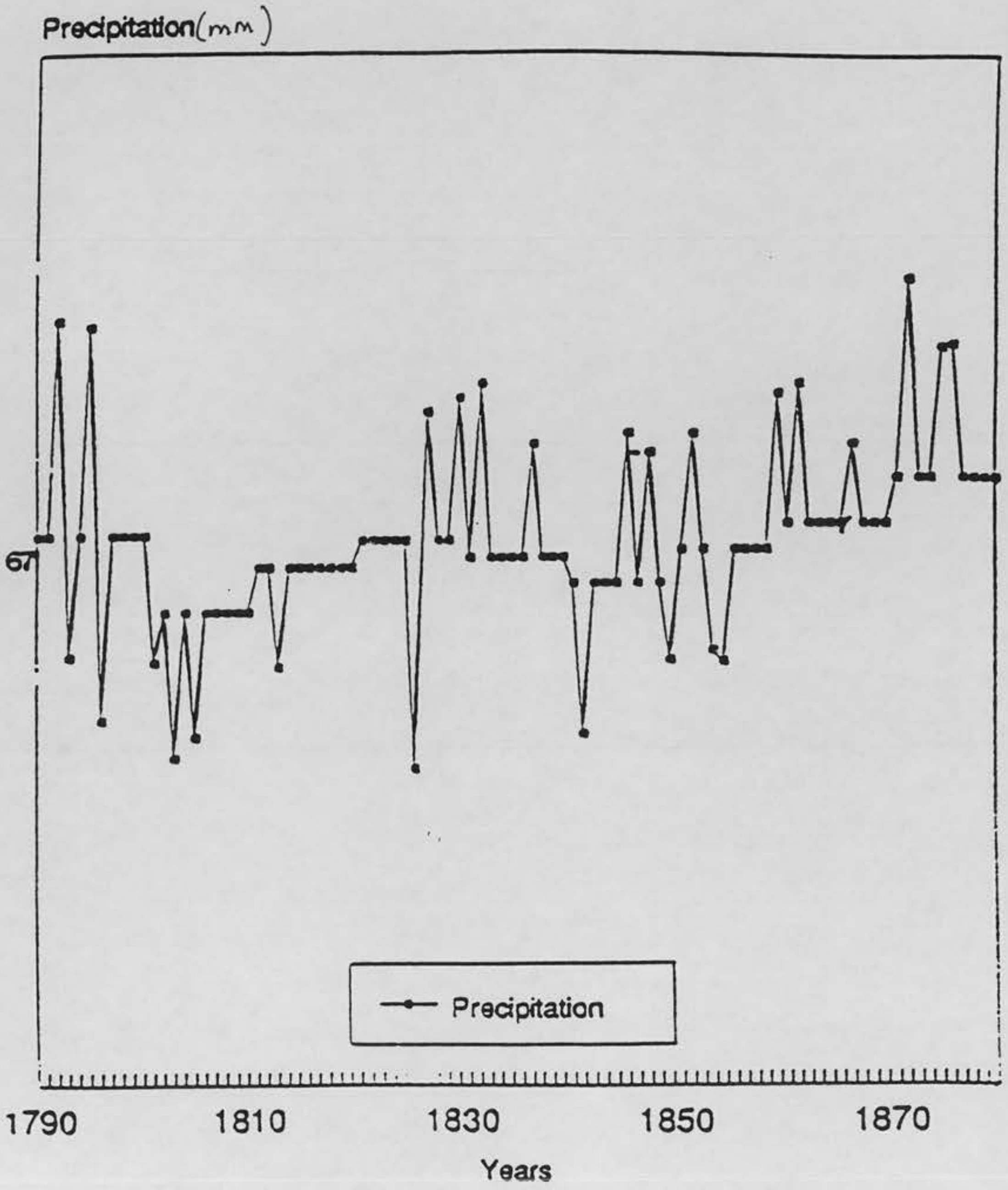


Fig. 5.6 Decennial Mean Precipitation and Extreme Precipitation Events



SUMMARY

The principal findings of this section suggest that with increased temperatures, there is likely to be slightly less variability in inter-annual temperature and little or no change in the magnitude of the fluctuations. In this case, variability increases with decreasing temperature. The current work supports Lamb (1977) who states that there is 'enhanced variability of temperature from spell to spell' during the Little Ice Age. There is likely to be a small increase in variability in precipitation. However, because temperature and precipitation are so poorly correlated, the increase in variability would be negligible. It is impossible to estimate the number of extreme temperatures or precipitation events, as there appears to be little or no relation between extreme values and mean temperature and mean precipitation. There are decades of very high and low extreme values, with little change in decadal temperature or precipitation; this is in agreement with Parry (1978) and Parry et al. (1985).

In conclusion, the historical analogue approach proves a possible means of predicting the effects of global warming in south-east Scotland. However, the method does have its limitations.

First, present-day warming may have no direct historical analogue. There is a problem in comparing the mechanisms of present-day climatic change with past perturbations. It is largely assumed that present-day warming results from increases in the greenhouse-gas content of the atmosphere, but it is still possible that it may be part of longer-term natural cycles. Past climatic disturbance may be related to Milankovitch forcing, sunspot activity, vulcanicity, tectonics or glacial processes. Specifically, in the northern hemisphere, global climatic disturbance can be associated with (1) changes in the position of the polar front and with (2) changes in the position and the intensity of cyclones. However, despite the differing causal mechanisms, there are certain tendencies associated with global climatic change which we can reasonably expect to be similar, whatever the initial cause.

Secondly, it is arguable that a prediction of precipitation, which is based on green-house gas projected warming, is invalid. This is because the historical analogue approach fails to take into consideration a possible increase in cloud cover with warming. With greater cloud cover, more precipitation would be expected.

Despite these limitations, it is suggested that the historical analogue approach is useful. Presently, it is the only method which allows prediction at a regional scale. Until new methods are devised or GCMs improved, the historical analogue has a purpose.

IMPLICATIONS FOR HUMANKIND

It has long been recognized that humankind is exceedingly vulnerable to perturbations in climate (Schneider et al. 1976, 1978). Global warming studies have predicted the socio-economic impact of changes in temperature upon precipitation, soil moisture, the frequency of extreme events, tropical storms, mid-latitude storms, sea-level rises, storm surges, ecosystem and structure (The Meteorological Office 1990). However, the greenhouse effect has been treated, in general, as a scientific problem, rather than a phenomenon that may disrupt people and societies on a large scale (New Scientist 1990).

In Britain, the primary and earliest effect of the predicted climatic change is likely to be on plant life, as the combination of elevated temperature and an increased concentration of carbon dioxide will have a forcing effect on plant growth (Parry et al. 1989).

IMPLICATIONS FOR AGRICULTURE

First, warmer temperatures would bring greater accumulated warmth, measured in day-degrees C. For the expected rise in temperature, the limit of agriculture was found to rise to 477m. This is far above the limit of arable agriculture today.

Second, decreased precipitation, however slight, is likely to be beneficial to arable agriculture. In south-east Scotland, excess moisture has been an agricultural problem for centuries. As early as the Iron Age, rural peoples used ridges as a means of drainage (Bowden et al. 1989). Later, ridge and furrow was used for the same purpose and finally tile drainage was encorporated in the 19th century (Parry 1972). A slight decrease in precipitation could only be viewed as advantageous.

Third, with less variability and warmer temperatures, the sizes of crop yields are likely to increase and the likelihood of an outright harvest failure to decrease.

IMPLICATIONS FOR HEALTH

Awareness of the potential effects of global warming on health has increased recently (Table 5.1). At least twelve articles in medical journals have been written on the topic in the past three years, compared with only two articles written in the previous twenty-two years (Silver Platter Information Systems 1990). Unfortunately, the subject has been poorly served by highly generalised and inaccurate predictions. For example, Haines (1991) conveys the impression that adverse health effects would predominate with global warming. He suggests, for example, that mortality would increase with warmer summers. Keatinge (1991) shows, however, that all countries experience higher mortality in winter rather than in summer; therefore, the direct effect of moderate global warming on mortality should be beneficial. It is important to address the role of climate because the control of an infectious disease requires an understanding of the causative agent, the vector, the host and the environment in which transmission occurs (Daur 1991).

In view of the current awareness of the possible effects of global warming on health, it seems useful to narrow the area of speculation that surrounds the role of climatic change and health. This section does so, by

Table 5.1

Table Showing the Increasing Importance of the Issue, Global Warming and Health

Year	Number of Articles Published
1991	7
1990	1
1989	3
1988	1
1985-87	0
1984	1
1982-83	0
1974-79	0
1970-73	1
1966-69	1

Source: Silver Platter Systems (1990).

Table 5.2

Monthly Temperatures for 1951-80 and the Predicted Temperatures for 2025 for Edinburgh

Month	Edinburgh's X Monthly Temp. (1951-80)	Edinburgh's X Monthly Temp.(2025)
J	3.3	3.2
F	3.5	4.1
M	5.2	5.2
A	7.4	7.9
M	10.2	10.9
J	13.2	14.5
J	14.7	16.1
A	14.5	15.7
S	12.7	13.2
O	9.9	9.3
N	5.8	5.6
D	4.3	3.0

Source: The Meteorological Office (1989) and Duncan (In press) focusing sharply upon regional climatic change and its effect on communicable disease. Specifically, this section aims to demonstrate: (1) the changes that may result from increased warming in south-east Scotland; and (2) what effects these changes may have on the incidence rates of two communicable diseases, namely Lyme disease and leptospirosis.

LYME DISEASE

Lyme disease, or borreliosis, is caused by the spirochaete Borrelia burgdorferi. The disease vector in Europe is the hard-backed sheep tick, Ixodes ricinus (Walker et al. 1989). Hosts of the disease include deer, racoons, mice and other rodents and man (Parke 1987). The preferred environment of these ticks is moist, permanent vegetation, which provides a humidity higher than 80%, without which they perish. These ticks are found in abundant numbers in the Highlands and the Southern Uplands of Scotland. I.ricinus is also found in the Pennines, Lake District and the Cumbrian Dome, Wales and the Welsh Marches, south-western England, the New Forest, the Downs and Thetford Chase. The ticks are inactive when the temperature drops below -15^{0}C and are killed by heat (Walker et al. 1989).

The disease is transmitted to man by the bite of a female adult tick, during the feeding period. This period lasts 7-10 days during two peak times of the year, from late March to late May or June (the spring rise) and from August to October (the autumn rise) (Walker et al. 1989).

The initial manifestation of the disease is a rapidly expanding rash or erythema chronicum migrans, around the tick bite; this rash is often accompanied by multiple secondary lesions. The disease often gives rise to malaise, fatigue, headache, fever, stiff neck, muscle and joint pain and swellings of the lymph nodes. After an interval of several weeks to several years, arthritic, neurological or cardiac complications may develop (Parke 1987).

The disease had been known in the United Kingdom, for the past 30 years, under the name Erythema chronicum migrans, as described by dermatologists. With increasing experience, the condition was recognised as a multisystem disease and rechristened Lyme disease in 1979 (Robbins et al. 1987). It is impossible to estimate the true number of cases, as some will have been missed when erythema chronicum migrans was absent, or when the skin disease was not seen by a dermatologist (Muhlemann 1986). The first case was reported in south-east Scotland in 1974. Thirteen cases were reported in East Anglia in 1984. Fifty-five cases were reported by dermatologists in the years 1981-86 (Walker et al. 1989). The first British case of the disease with neurological complications was reported in 1986; three further cases in 1987 demonstrated that this was not an isolated finding and suggested that the disease was more common than was first realised (Bateman et al. 1987).

LEPTOSPIROSIS

Leptospirosis, like Lyme disease, is caused by a spirochaetal organism. There are many different types, or serovars, of this organism (Ferguson 1990). Each serovar tends to be associated with different species of animals. Host animals include rats or other rodents, skunks, opposums, mongooses, hedgehogs, jackals, foxes, dogs, rabbits, hares, deer, migratory water fowl and some arthropods and fleas (Christie 1987). The most commonly found serovars in Britain include Leptospira hardjo, which is associated with cattle and L.icterohaemorrhagiae, which is associated with rats (Ferguson 1990). It is estimated that between 40 and 60% of rats carry the disease (Carson 1988).

The disease is spread to humans when leptospires, shed by an infected animal, enter the human host through a skin abrasion or intact mucous membrane, following exposure to an infected animal's urine or contaminated mud or water (Christie 1987). Those members of the population at risk can be split into two categories: (1) individuals who are occupationally at risk, such as farm hands, drainage and sewer workers, miners and fish and meat processors; and (2) individuals who are recreationally at risk, such as canoeists, windsurfers, swimmers and anglers (Carson 1988).

Successful transmission of the disease from rat to man depends on moisture. In dry soils, leptospires die in less than one hour; but in wet soils, they may survive for several weeks (Christie 1987). The optimum temperature for leptospires is 25°C. Leptospires are rapidly killed in acidic (pH 5.8) or alkaline (pH 8.0) conditions. The organisms are also killed by exposure to ultra-violet light, increasing salinity, detergents, disinfectants and temperatures of 50°C or more (Ferguson 1990). Lastly, the disease tends to be seasonal in nature, with peak incidences occurring from August-October (due to immersion in polluted water) for L.icterohaemmorhagiae and June-November/December for L.hardjo (Thakker et al. 1991).

The leptospires invade the bloodstream and cause widespread lesions. In humans, the disease may be sub-clinical (i.e. give rise to no symptoms) or produce a range of clinical manifestations. These range from a mild 'flu-like illness with a headache, fever, malaise, anorexia and muscle pain; to a severe, sometimes fatal illness: Weil's Disease. These particular patients present with jaundice, an enlarged liver, possibly meningitis and even renal failure (Godfrey 1990).

The first British case of the disease was recognized in 1922. Between 1933-48, there were 983 reported cases of Weil's disease. 3385 cases have been reported in England and Wales from 1937-89. These figures probably under-estimate the true incidence of the disease, as detailed data is not available (Ferguson 1990).

Dr. Ferguson (pers. comm. 1991) reports that no increasing trend in incidence has been observed over the last decade in England. In Scotland, there was a peak in incidence in the early 1970s, followed by a fall and then by another rise to the present day (Thakker et al. 1991).

Having established the background knowledge of both Lyme disease and leptospirosis and the present-day risk of each disease, it is now possible to address any possible link with climatic change. Specifically, it is necessary to establish what changes may result from increased warming in south-east Scotland and what effect these changes might have on the incidence rates of Lyme Disease and leptospirosis.

GLOBAL WARMING AND ITS POSSIBLE EFFECTS ON DISEASE IN SOUTH-EAST SCOTLAND

LYME DISEASE

Danielova (1990) has demonstrated that temperature significantly influences the development of ticks, but it does not influence their infection rate. Extrinsic factors, such as temperature and relative air humidity, are probably 'important at border values only' in the infection of ticks. Therefore, with increasing temperatures due to greenhouse-gas warming, the infection rate among ticks is unlikely to increase. The development of ticks, however, is likely to increase. The activity threshold of ticks is $7^{\circ}C$. The activity pattern of ticks is unlikely to increase with warming, because future temperatures will remain at or above the threshold $7^{\circ}C$ from April to November, as they do today (Table 5.2). This is in disagreement with Aitken (1991), who suggests that the pattern of activity is likely to alter due to generally higher temperatures. In light of the above, with warming, ticks would develop faster. Therefore, a rise in the disease rate may be anticipated.

Warmer temperatures would bring greater accumulated warmth: 1457 day-degrees C for $9.4^{0}C$ (the expected temperature) (Duncan, in press). With greater warmth, arable agriculture may become viable in climatically marginal areas. For the expected rise in temperature, the limit of agriculture was found to rise to 477m (Duncan, in press). This is far above the limit of arable agriculture today. If farming really were to take place at these new altitudes, a new niche would become available to the ticks. These fields would provide an ideal microclimate for the ticks - as they are cool, moist and under relatively permanent vegetation. Farms have proven to be a good source of tick populations and Lyme Disease. Baird et al. (1987) demonstrated a high prevalence of antibodies (indicating Lyme Disease) in farmers in Wigtownshire. In summary, an increase in disease rate may be expected due to an increase in available niches for ticks.

The historical analogue approach in south-east Scotland suggests that with greenhouse-gas warming, there is likely to be a slight decrease in precipitation. However, because temperature and precipitation are so poorly correlated here, ($r = -0.178$), the decrease would be negligible. Therefore, ticks are unlikely to disappear from their moist environment in the Southern Uplands. This conclusion differs from that of Aitken (1991), who suggests that the 'markedly drier summers' could result in the ticks disappearing from some areas.

In summary, an increase in the disease risk may be expected because: (1) ticks are likely to develop faster; (2) new niches are likely to be available and (3) ticks are unlikely to disappear from their present environment.

LEPTOSPIROSIS

Increased winter temperatures are likely to increase the number of rats, because the breeding season is extended and the natural food supply increases. A 20% increase in the number of rats in England and Wales in 1988-1989 was attributed primarily to the second warmest winter since records began (I.E.H.O. 1990). With a greater number of hosts, the disease risk is likely to increase; for Agaev (1990) demonstrated that the epizootic process has been found to depend on the number of animals in the population.

It has been shown that, with warming, summer mean monthly maximum temperatures may reach 25^{0}C, or more. Temperatures of 25^{0}C are optimum for the survival of leptospires outside the host. Therefore, with increased warming, more leptospires are likely to survive; this is likely to increase the disease risk.

In summary, there is likely to be a greater risk of L.icterohaemorrhagiae infection due to: (1) the greater number of hosts for pathogenic leptospires; and (2) optimal environmental conditions, such as temperatures of 25^{0}C and wet conditions, for the survival of leptospires.

CONCLUSIONS

The historical analogue approach is a useful approach to the prediction of climatic change in a region like south-east Scotland; although, the method does have its limitations.

With increased temperature due to greenhouse-gas warming, there is likely to be: slightly warmer winter temperatures; and substantially warmer summer temperatures with summer mean maximum monthly temperatures of 25°C, or more. There is likely to be slightly less variability in inter-annual temperature and little or no change in the magnitude of the fluctuations. There is likely to be a minimal increase in variability in precipitation; however, because temperature and precipitation are so poorly correlated, the increase in variability would be negligible.

Moreover, the historical analogue provides sufficient detail to link climate with agriculture and communicable disease. The increased warming is likely to result in a shift of the cultivation limit to 477m. Decreased precipitation, however slight, is likely to be beneficial to arable agriculture; excess moisture has been an agricultural problem for centuries. Finally, it is concluded that both Lyme Disease and leptospirosis are likely to increase with global warming.

CHAPTER 6: CONCLUSIONS

CONCLUSIONS

This thesis draws the following conclusions:

(1) ON CLIMATE

First, a mean monthly temperature record was established for fifty-year periods for Edinburgh, for the millenium 800-1900 AD. This is the first such record in Scotland. This record of long-term climatic change shows the same trends as Lamb (1977): the Medieval Warm Epoch, 1150-1300 AD; the climatic worsening, 1300-1500 AD; the temporary return to a warmer climate, 1500-1550 AD and a general change towards higher temperature, from 1700 AD onwards. This record is more representative of Scotland's temperature than former reconstructions from central England because: (1) it has been adjusted to be representative of Edinburgh; and (2) it has monthly values which are calibrated with an instrumental record in Edinburgh.

In addition to this record of secular climatic change, a record of short-term climatic change was also reconstructed. A mean annual temperature record for Edinburgh was established, for the years 1659-1763 AD. This record extends back Mossman's (1896) mean annual temperature record for the years 1764-1896 AD.

These records of short-term, medium-term and long-term climatic change provide sufficient detail to assess the influence of climate on agriculture and disease in Scotland.

Precipitation for Scotland, over the last millenium, was estimated using Lamb's (1977) high summer wetness/ dryness indices and rainfalls as percentages of the 1916-50 averages for England and Wales, 800-1950 AD. This is justifiable because areas in England and Wales can be matched to approximately comparable areas in Scotland. For example, the English Lake District and the Welsh Mountains have similar precipitation patterns to the Scottish Highlands.

The former assumption that summer temperature and summer precipitation are closely related in Scotland, has been shown to be erroneous.

(2) ON TREE-RINGS

One of the most promising techniques for reconstructing temperature and precipitation is tree-ring analyses. A critical comparison of oak tree-ring indices and historical instrumental weather records produced surprising conclusions. These were as follows. None of the three tree-ring chronologies from Blickling, Bath, or Oxford should be utilized in the reconstruction of past seasonal or annual temperature and precipitation. This is because: (1) the ring-width series all show poor correlations with instrumental temperature and precipitation measurements; and (2) temperature and precipitation, at best, only account for 2.76-12.18% of the total variation in ring width. Any climatic reconstructions would be extracting more information than the value of the data justifies.

Multi-site reconstructions of past climate from tree-rings appear to be more accurate than individual site reconstructions.

(3) ON CLIMATE-HUMAN RELATIONSHIPS

AGRICULTURE

The upper limit of cultivation does shift in relation to secular climatic change as Parry suggested. But, this study suggests that the cultivation limit has shifted 75m over the past 800 years. It is higher than calculated by Parry and it fluctuates by only half the amount calculated by Parry.

DISEASE

It is suggested that climate, from the short-term through to the long-term, played a role in both the cause and prevention of the spread of plague and malaria in Scotland. The climate prior to the mid-fourteenth century was not too cool to discourage rats, but it may actually have been too warm and dry for fleas to survive. In the north and west, however, cool temperatures and high humidity may have helped to prevent the spread of disease. During the Little Ice Age, ships continued to carry plague rats into ports, but low temperatures inhibited the spread of rats and fleas and hence of plague.

Scotland's average temperatures, from the Medieval Warm Epoch through to the Little Ice Age, were suitable for the spread of malaria. Malaria outbreaks coincided with wet summers. Precipitation was insufficient in the Medieval

Warm Epoch to provide the necessary aquatic habit for the mosquito. High summer temperatures over 15°C are linked to malaria outbreaks in the following year.

It is suggested that ergotism was not responsible for the Scottish witch-crazes. The climatic conditions were ideal for the development of ergot. However, neither rye nor wheat, the cereals chiefly responsible for the disease, was likely a significant part of the diet of the 16th-17th century Scots.

(4) ON THE HISTORICAL ANALOGUE APPROACH

The historical analogue approach proves to be very useful in predicting the effects of global warming in south-east Scotland. The approach is the only method which allows prediction at the regional level. Until GCMs are improved or new methods are developed, the historical analogue approach serves a purpose. The method, however, does have its limitations.

With increased temperature due to greenhouse-gas warming in south-east Scotland, there is likely to be slightly less variability in inter-annual temperature and little or no change in the magnitude of the fluctuations. There is likely to be a minimal increase in variability in precipitation; however, because temperature and precipitation are so poorly correlated, the increase in variability would be negligible.

The predicted warming is likely to have some impact upon humans. The increased warming is likely to result in a shift of the cultivation limit to 477m. Decreased precipitation, however slight, is likely to be beneficial to arable agriculture; excess moisture has been an agricultural problem for centuries. And the incidence of various communicable diseases is likely to alter. Both Lyme Disease and leptospirosis are likely to increase with global warming.

IMPLICATIONS

First, the new, mean monthly temperature record established for Edinburgh for the years 800-1900 AD, may be used to reconstruct mean monthly temperatures in fifty-year periods for the last millenium for other Scottish regions. This may be done in the following manner. Comparisons may be made between the mean monthly temperatures from weather stations throughout Scotland and Edinburgh's average monthly temperature for the period 1951-1980. Then the differences between the records may be added or subtracted from the new Edinburgh record, to create regional records of temperature for the last millenium. These resulting Scottish regional temperature records may be used in: (1) the study of climate-human interactions and (2) the creation of historical analogues for the effects of global warming.

The new, more reliable methodology for calculating the altitudinal shift in cultivation, which was established in Chapter Three, may be applied to regions throughout Scotland. Care, however, must be taken to assure a suitable lapse rate is used for each of the different regions. This methodology may also be applied to the prehistoric past.

The approach used in Chapter Four, to study the important issue of the relationship between climate and disease, especially for epidemic disease, may be used: (1) for other diseases in Scotland; and (2) for other regions of the world. There are further important instances of this relationship to be considered; such as disease-related crop failures, as occurred in the European potato blight of the 1840's (Lamb 1977); and other animal diseases. There is considerable scope for further work in this area.

The historical analogue approach may be applied to other regions of the world, where sufficient data sources exist. If the records are sufficiently detailed, links between climate and humans may be investigated.

It is hoped that the methods developed here, in earlier chapters, will be utilized and improved upon by others. This study only succeeds in narrowing the area of uncertainty that surrounds the issues of climatic change in agriculture and disease. It does not, and cannot, provide a definitive statement on the subject.

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SCOTS AND GAELIC WEATHER PROVERBS: A broad correlation with regional weather

By Kirsty Duncan

Department of Geography, University of Edinburgh

THROUGHOUT history, the limited arable lands of Scotland have been extensively settled. Prevailing weather conditions have determined to greater or lesser degrees the survival of previous generations. This dependence on the natural environment fostered the development of a considerable folklore about the procession of the seasons and daily weather patterns. In an essentially illiterate society, this wisdom was then imparted to future generations via the spoken proverb. A broad correlation between weather proverbs and weather patterns would have allowed farmers to predict meteorological changes with relative accuracy and alter their farming practices accordingly.

This paper aims to: (1) test critically the possibility that a broad correlation exists between weather proverbs and weather patterns; (2) determine the extent to which farmers adapted their farming practices to the ever-changing weather patterns; and (3) extend this correlation (of proverbs and weather conditions) to contrast the significantly different weather conditions which prevail in the Scots-speaking, more climatically continental east of Scotland and the Gaelic-speaking, more climatically maritime west.

SEASONAL CORRELATIONS

In Scotland, most plants cease to grow in December, January and February: a period aptly described as:

"Am mios marbh."
(The dead month: December–February.)
(MacDonald 1926)

But this is the time of year when farmers begin searching for omens regarding the new year. In eastern Scotland:

"If the grass grow in Janiveer,
'Twill be the worse for't all the year."

"A' the months o' the year, curse a fair Februar."
(Chambers 1841)

That is, a warm January and February was believed to be a portent of a cold year. Table 1 shows the results of correlation analysis of Edinburgh's monthly and annual temperatures (Mossman 1896) for the period 1764–93. This is an optimum period of time, 30 years, over which to assemble data for a climatic description (Meteorological Office 1989). This period

Table 1 Each month's mean temperature correlated with mean annual temperature for Edinburgh for the period 1764–93

MONTH	r VALUE
January	0.282
February	0.710
March	0.612
April	0.382
May	0.445
June	0.455
July	0.667
August	0.586
September	0.426
October	0.294
November	0.301
December	0.089

was chosen randomly. The 30-year period does not pertain to a specific climatic period, nor does it correspond to the dates of the proverbs. The Gaelic proverbs can only be dated approximately. The Scots proverbs may possibly be dated using the *Scots Dictionary* by looking up specific weather words: Scots words are given possible dates of use.

From Table 1 it is apparent that January's mean monthly temperature is a very poor predictor of mean annual temperature: the correlation coefficient, r, was only 0.282. February's mean temperature, however, is the most accurate predictor of mean annual temperature with an r value of 0.710. February's usefulness as the predictor for the year is well noted in Scottish proverbs: there are more sayings about this one month than in all the other weather proverbs put together (Chambers 1841).

Despite the rural population's success in ascertaining February's predictive power, these agriculturists incorrectly determined the direction of the relationship. February's mean monthly temperature is positively correlated with mean annual temperature. Therefore, if February was warm, the year, on average, should have been warm as well. However, it is generally conceded in popular sayings across Scotland that good weather in February is an unfavourable symptom of what is to come (Chambers 1841). In the east:

"As lang as the bird sings before Candlemas, he greets after it."
(Hislop 1868)

In the west:

"Chan eil port a sheinneas an smeorach 's an Fhaoilleach, nach aoin i mu'un ruith an t-Earrach."
(For every song the mavis sings in February, she'll lament 'ere Spring be over.)
(Nicolson 1951)

From Table 2 it is obvious that warmth in February is a good omen of what lies ahead: all the correlations are positive. Therefore, a warm February does not suggest a cool spring (March, April, May) as the proverbs suggest. In fact, February's mean monthly temperature, in general, is very poorly correlated with spring temperatures. The r values for April and May are only 0.090 and 0.145 respectively. However, the r value for February and March temperatures is 0.443 (this is the second highest value of all the correlations). Despite this fact, one is just as likely to ascertain March's weather by simply guessing.

Despite February's positive correlation with the mean annual temperature, February warmth may be a poor omen of what is to come. If February is warm, precipitation is likely to fall as rain rather than snow. Rain spoils young seed and grasses, whereas snow protects them. A lack of snow cover and hence soil warmth lead to: fracturing of the root systems, declining sucking power of the roots, slowing of the growth and development processes, and possible death (Ventskevich 1961). The resultant reduced yields would make the rural population the "worse for't all the year". Snow also acts as an accumulator of winter precipitation, thereby increasing the moisture reserves of the soil (Ventskevich 1961).

TABLE 2 February's mean temperature correlated with each month's mean temperature for Edinburgh for the period 1764–93

MONTH	r VALUE
January	0.292
March	0.443
April	0.090
May	0.145
June	0.104
July	0.403
August	0.498
September	0.226
October	0.200
November	0.028
December	0.063

Rainfall, on the other hand, is likely to run off the frozen soil, thereby decreasing the stored soil moisture. Hence, the following observations:

"Underwater dearth; under snow breath."
(Chambers 1841)

"February, fill the dyke, be it black, or be it white.
If it's white, it's the better."
(Carmichael 1957)

The severe character of March in the Scottish climate is noted with some force:

"March said to Averil...(of March 18, 19, and 20)
The first o' them was wind and weet;
The second o' them was snow and sleet;
The third o' them was sic a freeze."
(Hislop 1868)

Conditions in spring may be more unpleasant than in midwinter. The north-easterlies that often prevail in Scotland in spring give rise to cold unstable showery air (Paton 1951). The unstable nature of spring in the east is emphasised in:

"March comes wi' adders' heads and gangs wi' peacocks' tails."
(Henderson 1832)

"Till May be out, Change nae a clout."
(Chambers 1841)

If the wind veers to the north-north-east, the change is sufficient to bring showers or snow flurries over all south-eastern Scotland. Hence, of spring:

"Snow liest ahint the dike, Mair may come and fill the furrows."
(Hislop 1868)

Despite March's harsh nature, cautious farmers strongly advocate that spring work should be done in March (Geddes 1955). This is because Scotland is slow to 'warm up' in spring (Paton 1951); in order to have enough warmth for crops, it is necessary to sow early. In the east:

"A peck o' March dust is worth a peck o' gowd."
(Chambers 1841)

This proverb shows that seeds are already sown in March. Dry weather is hoped for because seeds and new plants are killed by smothering if they stand in water for a long time. However, by April the seeds have sprouted and require moisture:

"April showers bring May flowers."
(Hendry and Stephen 1982)

If plants fail to get the moisture they require, drought may seriously retard seed germination.

In the west, early work was also insisted upon:

"Cia air bith mar bhios an sian, Cuir an siol anns a' Mhairt."
(Be the weather what it will, Sow the seed in March.)
(Nicolson 1951)

First, because spring comes late to the islands, the ground, but recently sown, is most susceptible to parching:

"Cha tig Geamhradh gu cul Calluin, no Earrach gu cul Fheill Paruig."
(Winter comes not till after New Year, nor Spring till after St. Patrick's Day.)
(MacDonald 1926)

Total rainfall in the west for the five months from February to June is only 55–60 per cent of that from September to January. The seasonal difference is less marked in eastern Scotland (Meteorological Office 1989); hence, there is no risk of parching. Figure 1 shows that in Tiree (taken to be a representative station of the Hebrides) April, May and June receive the

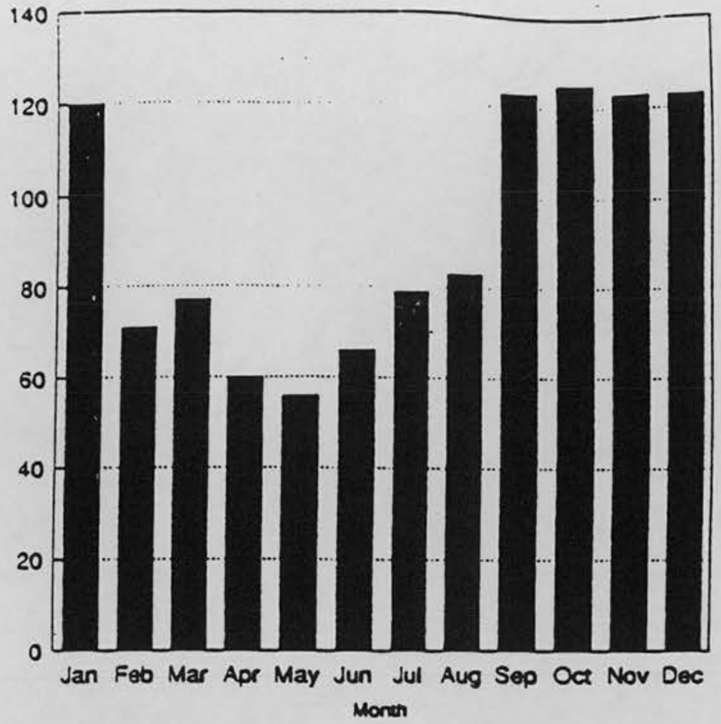

Fig. 1 Mean monthly precipitation (mm) for Tiree for the period 1951–80 (from Meteorological Office 1989)

least amount of precipitation of all the months of the year. Therefore, if the growth is far enough advanced to form natural cover and the roots penetrate deep enough into the soil, a dry spring is not so dangerous. Also, because the islands remain subject to the occasional frost (the Western Isles experience, on average, 49 days per year with air frost (Meteorological Office 1982)) much growth is not wished for:

"Aiteamh na gaoth tuath, sneach is reodhadh anns an air."
(The thaw that comes while north winds blow will followed be by frost and snow.)
(Nicolson 1951)

After spring's wealth of proverbs, summer seems to be sadly lacking in lore. Perhaps this is because Scotland's summer climate is well suited to particular types of agriculture. First, temperature peaks in June, July and August in both the east and the west; thus the greatest summer warmth coincides with the ripening period. The meteorological conditions prevailing when the grain is being formed have a great deal of influence on the absolute weight of the grain (Ventskevich 1961). Second, the hours of bright sunshine climax in May, June and July in the east, and April, May and June in the west (see Fig. 2). Plants such as wheat, oats and barley will develop rapidly and flower early when days are long. And third, precipitation, in general, is of a sufficient magnitude. However, sometimes a lack of moisture threatens agriculture in both the east and the west:

"A dry summer ne'er made a dear peck."
(Chambers 1841)

"B'olc an airidh gu'n dearadh an turadh dolaidh."
('Twere a pity that dry weather should do harm.)
(Nicolson 1951)

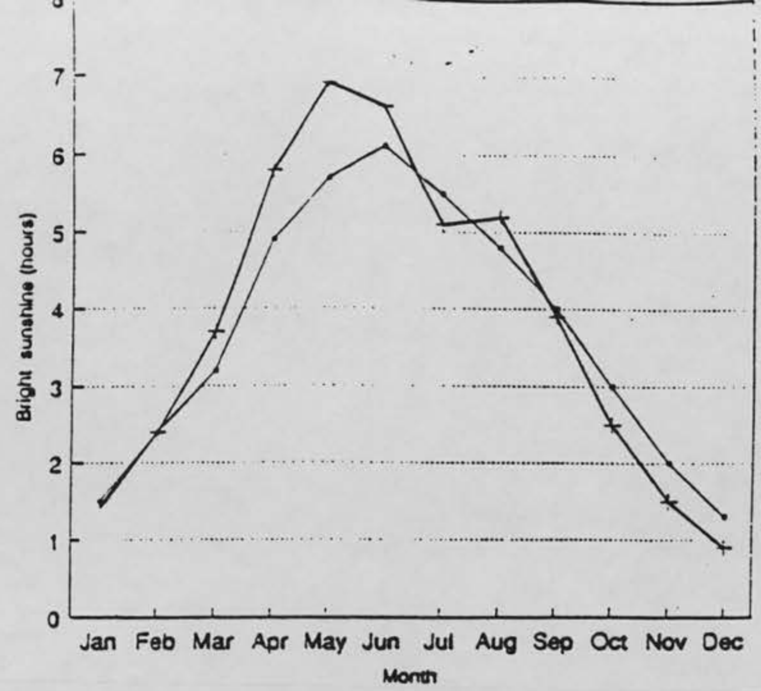

Fig. 2 Monthly averages of daily bright sunshine for Edinburgh (lines with squares) and Tiree (heavier lines with crosses) for the period 1951–80 (from Meteorological Office 1989)

A deficiency or absence of precipitation causes the ploughed horizon to dry up, hampers the supply of moisture to the plants, damages plants and reduces yields (Ventskevich 1961).

Autumn, like summer, has few proverbs attached to it. This is probably because the crops have ripened and require only harvesting. Farmers do not need climatic signs for harvesting; the proper time for reaping is obvious from the condition of the fruit. In the west, autumn is threatening in that the weather is most variable:

> "*Is ioma car a thig air an oidch'fhad Fhoghair.*"
> (Many a turn comes in the long autumn night.)
> (Nicolson 1951)

The greatest percentage of rain falls at this time (see Fig. 1). Frequent and heavy rains, falling when grain crops and grasses are harvested, can result in heavy losses (Ventskevich 1961).

In summary, what makes a good harvest in the east and west differs significantly due to their different climates. In the east, the season calculated to produce a good harvest is:

> "*A frosty winter, and a dusty March, a rain about April,*
> *Another about the Lammas time, when the corn begins to fill,*
> *Is weel worth a pleuch o' gowd, and a' her pins theretill.*"
> (Chambers 1841)

In the west:

> "*Geamhradh reodhtanach, Earrach ceothanach,*
> *Samhradh breac-riabhch, 'us Foghar geal griannach,*
> *Cha d'fhag gorta riamh 'an Alba.*"

(Frosty winter, misty spring,
Chequered summer and sunny autumn,
Never left dearth in Scotland.)
(Nicolson 1951)

Both regions hope for a frosty winter to protect young seeds. In spring the east desires dryness to prevent soaking, whereas the west wants wetness to prevent parching. Both areas wish for sunny summers with adequate rain. The west, which suffers from heavy precipitation in the autumn, requires dry weather to prevent damage to crops while harvesting.

The rhythm of work not only responded to the seasons' weather, but also to the day's weather. Therefore, Scotland's agricultural forefathers had to learn to predict the daily weather accurately. Of all the types of weather, the wind has the most proverbs. This is because the wind brought the weather; if the wind changed, so too did the weather. In the west they say:

"*Is buaireadh gach sine a'ghaoth.*"
(All change of weather is due to the wind.)
(Nicolson 1951)

In the east the four strong winds are said to bring the following weather:

"*When the wind's in the north,*
Hail comes forth;
When the wind's in the wast,
Look for a wat blast;
When the wind's in the soud,
The weather will be fresh and good;
When the wind's in the east,
Cold and snow comes niest."

"*Nae weather's ill, And the wind bide still.*"
(Chambers 1841)

This compares well with what is said in the west:

"*Gaoth tuath, fuachd 'us gaillronn.*"
(North wind, cold and tempest.)

Gaoth niar 'an deigh uisge reamhar."
(West wind after heavy rain.)

"*An uair a bhios a'ghaoth air challion a deas i.*"
(When there is no wind, seek it in the south.)
"*An uair a laidheas a'ghaoth, 's maoth gach sian.*"
(No weather's ill, if the weather be still.)
(Nicolson 1951)

Each wind does, indeed, bring different characteristics. When the wind is from the north, cold, unstable, showery or frosty air sweeps over the country. Westerly winds, originating over Canada and passing over the North Atlantic, give heavy showers along the west coast of Scotland; these winds sometimes succeed in penetrating to the east. When the wind is from the south, airmasses move directly northward; thus it brings warmth and little precipitation (the hills in northern England and southern Scotland effectively reduce precipitation). Winds from the east come directly from the Continent; thus it is cold in winter and hot in summer.

In conclusion, Scotland's rural predecessors learned to ascertain daily weather fairly accurately. However, they appear to have had difficulty with some of their longer-term predictions. Even with all our technological advances, this still holds true – our predictions are not accurate for more than about five days (Schneider 1989). Despite the earlier Caledonian people's success in reckoning their regional weather, the following lines hold as true today as they did in the past;

"To talk of the weather, it's nothing but folly,
For when it's rain on the hill, it may be sun in the valley."
(Chambers 1841)

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The possible influence of climate on the bubonic plague in Scotland

irsty Duncan

epartment of Geography, University of Edinburgh, Drummond Street, Edinburgh EH8 9XP

BSTRACT: The role of climate as a possible factor the spread of bubonic plague in Scotland is nsidered. It is concluded that the climate prior to e mid fourteenth century was not too cool to scourage rats, but that it may have been too warm d dry for fleas to survive. In the north and west of cotland, however, cool temperatures and high umidity may have helped to prevent the spread of the disease. During the Little Ice Age, ships continued to carry plague rats into ports, but low temperatures inhibited the spread of rats and fleas — and hence of plague.

KEY WORDS: Plague, Climatic change, Medieval Scotland

ITRODUCTION

ie 1340s ushered in one of history's most infamous t-borne pandemics — the Black Death (Hendrickson 83). This 'Destroying Angel' reached Scotland in 49. The Scottish people blamed clouds or miasmas ising from the earth, volcanic eruptions, rthquakes, comets, dogs and cats, drunkards, avediggers, cripples, strangers, gypsies, beggars, pers, and Jews for the 'Great Dying' (Hamilton 81).

Today, disease is seen as a product of the interaction tween a disease agent, a disease host, and the vironment (Brandford 1977). In the case of bubonic ague, the agent is the bacillus, *Yersinia pestis*, and e host is the rat (*Rattus rattus*) or man (Hendrickson 83). The relationship between the disease agent and sease host is well understood. Bubonic plague is used by the invasion of a rat by *Y. pestis*. The cillus multiplies rapidly in the infected animal; thus, ien a rat flea, *X. cheopis*, feeds, it sucks up large mbers of bacteria from its blood meal. The bacteria ultiply rapidly in the flea's stomach until it is mpletely filled — the blocked flea. Because no more ood can pass the flea's blocked stomach, the flea ntinues to feed, but eventually regurgitates infected ood. The flea also defaecates as it feeds. As soon the rat dies, the fleas search out alternative hosts, or man. Thus, *Y. pestis* is emitted onto the victim's n and the bacteria enter into circulation via the new ncture wound. Once bubonic plague becomes mpant amongst humans, another clinical form, eumonic plague, may develop. This form of the sease is spread by droplet infection (Shrewsbury 77).

The role of environmental factors is more poorly derstood than the disease agent and disease host. rious environmental factors have been proposed to plain the spread of plague in Scotland, including er-crowding of towns, simple housing, poor nitation, and climate (Hamilton 1981). Historians ve favoured explanations involving over-population d inadequate disposal of refuse to the virtual exclusion of climatic factors. When climate is invoked as a causal variable for the great pestilence, no testing is made of the assumption, nor is proof provided. For example, Hamilton (1981) stated that Scotland's immunity to the plague until 1349 was due to her slightly cooler climate which did not encourage the rats which spread the plague.

Climate exerts a tremendous influence on the spread of bubonic plague. The Plague Research Commission (1908) concluded that the spread of rat and human plague is checked by temperatures over 26° C. This is because the plague-transmitting power of the individual flea is reduced. Furthermore, the disease cannot exist in epidemic form at temperatures over 27° C, as the flea's block is dissolved and the flea is cleared. Bacot (1911-14) demonstrated that a temperature range of 20-25° C was the most suitable for the development of *X.cheopis* at all stages.

Cold temperatures, as well as warm temperatures, also check plague. The Plague Research Commission (1908) showed that low temperatures (i.e. those under 10° C) limited outbreaks. First, this is because infected rats die more quickly with fewer plague bacilli in the blood. Thus, fewer fleas have the opportunity to acquire the infection. Second, low temperatures limit the vector efficiency and the general activity of the rat fleas. Third, healthy rats die more quickly at cool temperatures. Last, Bacot (1911-14) demonstrated that *X. cheopis* did not breed at all in cold weather; in cool weather, the breeding of a perfect insect may take months. Furthermore, the eggs of *X. cheopis* do not hatch below 12.8° C.

Moisture, like temperature, also limits plague. St. John Brooks (1917) showed that plague cannot maintain itself when the air is very dry. It has also been shown that excessively high humidity is adverse to plague (Hirst 1953).

In summary, the macro-climate plays an important role in plague transmission, but so too do the various micro-climates. The temperatures and humidities of rat burrows, clay walls, straw roofs, and slum huts will all affect the transmission of plague to varying degrees (Learmonth 1988). This paper limits itself to the examination of the macro-climatic influence only.

In view of the past failure to examine critically the effect of climatic influences on the spread of plague in Scotland, this paper aims to investigate the relationship. Specifically, the paper firstly demonstrates that Scotland's climate prior to 1349 was not too cool to discourage rats but in fact was too warm and dry for the fleas which spread the plague to survive. Secondly, it aims to provide an explanation for why plague continued to persist into the Little Ice Age despite the climatic downturn. Thirdly, it seeks to explain why plague may never have occurred in the west and north of Scotland.

METHOD

In order to investigate the relationship of climate and plague, a comparison was made between the climates of years with plague and those without. Before explaining the method used here, it is important to stress the limited documentary evidence for studying pre-seventeenth century plagues in Scotland. Because of the limitations of the sources, it is difficult to ascertain the scale and mortality of most outbreaks. It is also difficult to establish which were the most severe outbreaks in the fourteenth, fifteenth and early sixteenth centuries.

A mean monthly temperature record for Edinburgh (800-1900 AD) was utilised as the temperature record (Duncan forthcoming). Scotland experienced four major pestilences in 1349, 1362, 1380 and 1392. Plague continued to erupt in isolated towns from the fifteenth to seventeenth centuries, but the outbreaks were limited both in time and space (Shrewsbury 1977). (Again it is important to recognize the limitations of the sources. Because documentation relating to plague outbreaks in Scotland is far more abundant for urban than for rural areas, outbreak may not have been limited in both space and time.) Thus, the climate of the plague period, 1350-1400 AD, was compared to the climate of the preceding Medieval Warm Epoch (MWE) period (1150-1300 AD), when there were no recorded plagues.

In order to determine if the MWE was too warm and dry to support the fleas that carried the *Yersinia* bacillus, the following procedure was undertaken. Edinburgh's 1951-1980 mean monthly maximum temperature was used to predict monthly maximum temperatures for the historical period. This is because Edinburgh's mean annual temperature, 8.7° C, was the same as Edinburgh's mean annual temperature for 1350-1400 AD. In order to determine the maximum temperatures attained in that period, Edinburgh's 1951-1980 mean monthly temperatures were subtracted from the mean monthly maximum temperatures for the same period to determine the differences, which were then added to the 1350-1400 AD monthly temperatures. Lamb's (1977) summer wetness/dryness index was utilised to determine the amount of moisture for this time period.

Next, the relationship between the plague outbreaks of the fifteenth to seventeenth centuries and the coo climate was examined. Plague years were checke against Lamb's (1977) winter mildness/severity an summer wetness/dryness indices.

Lastly, the relationship between climate and locatio of plague outbreaks was critically investigated. Firs centres of plague outbreaks were mapped for th period 1350-1650 AD. Second, plague-tim temperatures for the north and west were calculated To determine the temperature in the north in 1350-140 AD, the following procedure was undertaken. First Nairn was taken to be representative of a Highlan weather station (Meteorological Office 1989). A comparison was made between its mean monthl temperature and Edinburgh's average monthl temperature for the period 1951-1980. Second, th difference between the two sets of figures was the either added or subtracted from Duncan's (forthcoming) temperatures calculated for 1350-1400 AD. The differences between the two weather station are assumed to have remained constant. Third, the temperature at 100 m a.s.l. was calculated in order to determine maximum temperatures in the Highlands The same procedure was also carried out for Tiree in order to obtain representative statistics for the wes of Scotland.

Table 1 Temperatures (°C) of the plague period (1350-1400 AD) and the pre-plague period (1150-1300 AD).

Month	1150-1200 AD	1200-1250 AD	1250-1300AD	1350-1400 A!
January	3.2	3.1	3.2	2.8
February	4.1	4.0	4.1	3.6
March	5.2	5.2	5.2	4.8
April	7.9	7.9	7.9	7.4
May	10.9	10.9	10.9	10.3
June	14.5	14.5	14.5	13.7
July	16.1	16.1	16.1	15.3
August	15.7	15.7	15.7	14.9
September	13.2	13.2	13.2	12.5
October	9.3	9.3	9.3	8.7
November	5.6	5.5	5.6	5.1
December	3.0	2.9	3.0	2.6

Source: Duncan (forthcoming).

RESULTS

Table 1 shows the temperatures of the plague perio (1350-1400 AD) and the temperatures of the precedin MWE non-plague period (1150-1300 AD). Table shows the maximum temperatures attained in th plague period. Table 3 gives Lamb's (1966) figures fc high summer rainfall for 1150-1300 AD and 1350-140 AD: the high summer wetness/dryness index is als presented for the same periods. Table 4 presents comprehensive listing of Scotland's plagues along wit Lamb's (1977) winter mildness/severity and summe wetness/dryness indices. Figure 1 maps the centres c plague outbreaks for the period 1350-1600 AD. Tabl 5 and 6 show the temperatures in the Highlands an west for the 1350-1400 AD and 1550-1600 AD period

Table 2 Edinburgh's calculated mean monthly maximum temperatures for 1350-1400 AD.

Month	Mean temperature (1951-1980)	Mean maximum (1951-1980)	Difference	Mean maximum (1350-1400)
January	3.3	11.6	8.3	11.1
February	3.5	11.4	7.9	11.5
March	5.2	13.7	8.5	13.3
April	7.4	17.6	10.2	17.6
May	10.2	20.6	10.4	20.7
June	13.2	23.4	10.2	23.9
July	14.7	23.3	8.6	23.9
August	14.5	23.1	8.6	23.5
September	12.7	21.1	8.4	20.9
October	9.9	18.3	8.4	17.1
November	5.8	14.3	8.5	13.6
December	4.3	12.4	8.1	10.7

Table 3 Lamb's (1977) high summer wetness/dryness index

	1150-1300 AD	1350-1400 AD
High summer rainfall as percentage of mean 1916-50 in England and Wales	85.3	105
High summer wetness/dryness index	8.8	10.9

Note: No precipitation information exists for Scotland.

DISCUSSION

In comparing the plague period, 1350-1400 AD, and the MWE non-plague period, 1150-1300 AD, and their respective climates, the following was apparent. Plague did not occur in the early warm period, but in the slightly cooler later period. This finding is in direct conflict with Hamilton's (1981) statement about Scotland — that the "slightly cooler climate (prior to 1348) did not encourage the rats that spread the plague".

In order to explain this finding, mean maximum monthly temperatures and measures of humidity were examined. (These temperatures were examined because all summer mean monthly temperatures fell within the climatic limits for rats and fleas.) The 1350-1400 AD summer monthly maximum temperatures (23.4°, 23.3°, 23.1°, and 21.1° C) all fell within the temperature range of 20-25° C. Bacot (1911-1914) showed that this temperature range was the most suitable for the development of *X. cheopis* (the fleas that most efficiently transmit the *Yersinia* bacillus) at all stages. The MWE's mean summer temperature was warmer by 0.8° C than the average summer temperature of the 1350-1400 AD period. Unfortunately, there was no way of accurately predicting the MWE's summer mean maximum monthly temperatures because no climatic data exist for a summer mean of 15.9° C in Edinburgh. However, if the same differences (i.e. mean maximum monthly temperature — mean monthly temperature) are used, the results are as follows: 24.4°; 24.7°; and 24.3° C. These temperatures probably underestimate the true temperature because with an increase in mean monthly temperature, there would be an accompanying rise in mean maximum monthly temperatures. Thus, temperatures exceeding 25° C would likely occur. The Plague Research Commission (1908) showed that the disease cannot exist in epidemic form at temperatures over 26° C. Furthermore, if temperatures rose to 27° C, the stomach block is dissolved (Hirst 1953). Therefore, it appears that the temperatures of the MWE may have been too warm to maintain an epidemic.

Table 4 Outbreaks of plague and Lamb's winter mildness/severity and summer wetness/dryness indices.

Year		Winter	Summer
1348		+2	10.5
1392		−2	11
1402	Stirling, Dundee	−3	11
1420		+4	7
1431	Edinburgh	−12	12
1432	Haddington		
1475	Edinburgh	+3	8
1493		−5	16
1498			
1505	Edinburgh	+7	7
1512			
1513	Dene	−2	7.5
1519	Edinburgh, Lothian		
1529	Edinburgh	+2	11
1546	Aberdeen		
1548	Perth	−2	8
1549	Edinburgh, Aberdeen, Stirling, Haddington, Berwick		
1580			
1584	Perth, Dysart, Kirkcaldy	−7	12.5
1586	Dundee, Niddrie, Dunse		
1587	Leith, Edinburgh		
1597	Esk Valley, Dalkeith, Newbattle, Inveresk, Musselburgh, Dolphinton, Ednam, Sprouston, Lyntoun	−5	11
1600	Findhorn, Dundee, Craill, Eglesham, Eastwood, Glasgow		
1602	Edinburgh		
1604	Edinburgh		
1606	Edinburgh, Stirling, Dundee, Perth, Glasgow	−10	11.5
1607	Edinburgh, Stirling		
1608	Dundee, Perth		
1609	Perth, Kinghorn, Inverkeithing		
1624	Edinburgh	−7	13
1635	Preston, Prestonpans	−5	11
1637	Nisbet Mill		
1644	Edinburgh, Borrowstouness, Kelso, Perth		
1645	Edinburgh, Glasgow, Paisley, Lanark, Peebles, Leith, Perth, Falkirk, Stirling, Dunfermline, Dysart, Galashiels	−3	11
1647	Brechin, Inverbervie, Largs, Dunblane, Menmuir, Aberdeen		
1648	Glasgow, Montrose		

Note: Winter mildness/severity is the number of unmistakably mild months (D,J,F) minus the number of severe months (D,J,F) per decade.

High summer wetness/dryness: each July or August with unmistakable evidence of frequent rain = 1; an unremarkable July or August = 0.5; dry month = 0. Total per decade.

Source: derived from Lamb (1977) and Shrewsbury (1977).

Warm temperatures and dryness of the air are adverse to plague epidemics. Brooks (1917) pointed out that a great increase in the drying power of the air

Table 5 Temperatures in Nairn (north/Highland) 1350-1400 and 1550-1650 AD.

Month	Nairn 1951-80	Edinburgh 1951-80	Difference 1951-80	1350-1400 100 m asl	1550-1600 100 m asl
January	2.9	3.3	−0.4	1.2	0.6
February	3.8	3.5	−0.3	2.8	2.1
March	4.9	5.2	−0.3	3.3	2.7
April	6.8	7.4	−0.6	5.6	5.0
May	9.6	10.2	−0.6	8.5	7.9
June	12.5	13.3	−0.8	11.7	11.2
July	13.6	14.7	−1.1	13.0	12.4
August	13.7	14.5	−0.8	12.9	12.3
September	11.9	12.7	−0.8	10.5	9.9
October	9.9	9.9	0	7.5	6.9
November	5.4	5.8	−0.4	3.5	2.9
December	3.9	4.3	−0.4	1.0	0.4

asl — above sea level.

Source: please see text.

Table 6 Temperatures in west Scotland 1350-1400 and 1550-1600 AD.

Month	Tiree 1951-80	Edinburgh 1951-80	Difference 1951-80	1350-1400	1550-1600
January	6.3	3.3	+3.0	5.8	5.2
February	6.4	3.5	+2.9	6.5	5.9
March	6.1	5.2	+0.9	5.7	5.1
April	7.0	7.4	−0.4	7.0	6.4
May	9.7	10.2	−0.5	9.8	9.2
June	12.3	13.3	−1.0	12.7	12.1
July	13.5	14.7	−1.2	14.1	13.5
August	13.2	14.5	−1.3	13.6	13.0
September	11.5	12.7	−1.2	11.3	10.7
October	9.4	9.9	−0.5	8.2	7.6
November	6.4	5.8	+0.6	5.7	5.1
December	6.2	4.3	+1.9	4.5	3.9

Source: please see text.

alone might bring an epidemic to an end, even if the temperature never rose above 26° C. Table 3 clearly shows that the MWE was much drier than the following plague period. Thus, the MWE's climate, with its warm temperatures and dry air, was not conducive to plague epidemics. In summation, it is suggested that temperatures in the period preceding 1349 were not too cool to support rat populations: rats are likely to have flourished in these conditions. However, it was too warm and dry to support *X. cheopis* fleas which harboured the disease. This is not to suggest that climate alone prevented plague in this period. Other factors surely played a role in the prevention of the disease.

Plague continued to erupt in the period from the fifteenth to seventeenth centuries, despite the climatic downturn of the Little Ice Age (LIA). Table 4 shows that winters became more severe from 1550 onwards, and summers became increasingly wet from the 1580s. Table 1 shows the temperatures of this cold plague period, 1550-1650 AD.

Bacot (1911-1914) showed that in cool weather, breeding of fleas may take months (up to 182 days) for some species; furthermore, he demonstrated that the eggs of *X. cheopis* do not hatch below 12.8° C. In the 1550-1650 AD period, fleas could not have hatched until June and they may not have matured for months. If fleas did mature, plague could not have maintained itself past September. The Plague Research Commission (1908) showed that with temperatures below 10° C, infected rats die more quickly with fewer plague bacilli in the blood. Thus, fewer fleas have the opportunity to acquire infection. Even healthy rats die more quickly at cool temperatures (Hendrickson 1983). In addition, low temperatures influence the vector efficiency and general activity of rat fleas (Hirst 1953). Thus, low temperatures check plague.

Figure 1 Plague centres in Scotland Source: derived from Shrewsbury (1977)

Despite the Little Ice Age's low-temperature check on plague, the disease continued to occur. Figure 1 shows the distribution of plague centres. Most centres were sea or river ports. One possible explanation is that cargo ships could have carried plague rats, which could have escaped into the towns. *X. cheopis* could easily have survived on the rats which migrated to warm houses. Plague could not have spread to neighbouring towns as the climatic conditions prevented the spread of rats and their fleas. Also, the cold winter temperatures of the LIA prevented plague from persisting from one year to the next. Only in 1607, 1608, and 1644, did plague carry over into the following year (see Table 4). It is likely that the winters did stop plague, but maritime influence probably caused the resurgence of the disease in Edinburgh, Stirling, and Perth.

The disappearance of plague in Scotland coincided

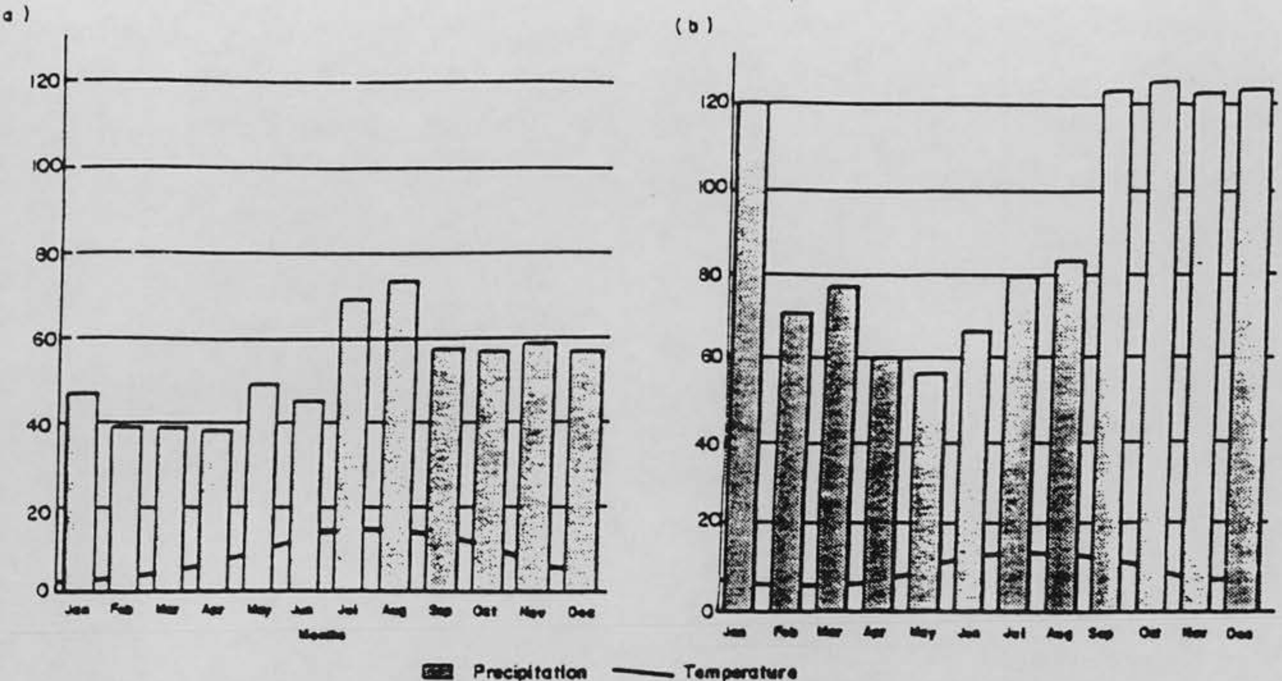

Figure 2 Mean monthly temperature and precipitation for (a) Edinburgh and (b) Tiree (1951-80) Source: Meteorological Office (1989)

vith the nadir of the LIA (1650-1700 AD). At such time, climatic conditions were not so bad as to radicate rats and fleas, but they may have discouraged he already-diminishing number of rats. Climate aided he eradication of plague, but it was not the limiting actor. Factors surely varied in importance from one hase to another. Improvements in both sanitation and orts' quarantine measures may well have had ignificant roles at this time (Hamilton 1981). Although plague persisted in eastern Scotland until 648, it scarcely affected the western and northern reas (Fig.1). Thus, plague occurred in the warmer and rier east. Figure 2 shows temperature and recipitation graphs for Edinburgh and Tiree. Iamilton (1981) utilised dispersed population and ifficulty of travel to explain the spatial distribution f plague, but he excluded climatic factors. Climate's nfluence on plague was implied by Sir Robert Gordon who wrote "Ther is not a ratt in Sutherland; and if ey doe come thither in ships, they die presently how oon they doe smell the air of that Cuntry". utherland was, apparently, too cold to maintain rat opulations.

The examination of the plague-climate relationship the north and west is shown in Tables 5 and 6. Jairn, at an altitude of 100 m a.s.l., experienced emperatures warm enough (i.e. temperatures above 0° C) for rats to survive from June to October in 350-1400 AD. Tiree, however, could only have upported rat populations from July to October. In 350-1400 AD, both Nairn's and Tiree's July and ugust temperatures would have allowed fleas to atch: the following cool months, however, would ave determined a long maturation period. Thus, few eas would have developed. In the LIA period, rats ould have survived only from June to August in Nairn and from July to October in Tiree. Temperatures never reached 12.8° C in Nairn. This implies that fleas could not hatch, mature, and spread disease. In Tiree, fleas could have hatched in July and August, but the ensuing cool temperatures would have prevented maturation. In summary, temperatures were too cool to support rat populations for any length of time and too cool to allow fleas to mature.

In addition to the cold, both the north and west experience high humidity and precipitation. Figure 2 compares the precipitation for Tiree and Edinburgh. Otten (1932) showed that excessively high humidity is adverse to plague. *X. cheopis* cannot breed in really damp environments. Therefore, in the north and west, the combination of cold and extreme wetness could have prevented the spread of plague. This is not to suggest that climate alone limited plague in the north and west. The dispersed nature of the population and the difficulty of travel in these areas would also have limited the spread of the disease (Hamilton 1981).

CONCLUSIONS

This paper demonstrates the importance of climate in influencing the spread and persistence of plague in Scotland. It is important to address climate's role because the control of an infectious disease requires an understanding of the causative agent, the vector, the host and the environment in which transmission occurs (Daur 1991). It is not suggested that climate alone caused or prevented the spread of plague: it was merely one factor.

In evaluating the chief climate-plague findings of the work, it is important to keep in mind the limitations of the documentary sources. This work, founded on the available sources (however imperfect) reaches the following conclusions. First, Scotland's climate prior to 1349 was not too cool to discourage rats, which spread the plague, but in fact was too warm and dry for the fleas which spread the disease. Second, cargo ships in the Little Ice Age carried plague rats into sea and river ports; cold temperatures prevented the spread of rats and fleas, and hence plague into neighbouring areas. Third, cool temperatures and excessive humidity helped to stop plague from spreading to the north and west of Scotland.

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A COMPARISON OF THE TEMPERATURE RECORDS OF EDINBURGH AND CENTRAL ENGLAND

By Kirsty Duncan

Department of Geography, University of Edinburgh

TODAY, there exist only two comprehensive instrumental temperature sets for all of Great Britain – G. Manley's (1974) Central England series (1659–1973) and R. Mossman's (1896) Edinburgh data (1764–1896). Much use has been made of the English data to reconstruct past warmth for all of Great Britain (but with the exclusion of the Scottish temperatures). Doubts have been expressed over the use of English records, particularly with respect to the study of climatic change in Scotland (Parry 1973). For example, Price (1987) states that, "The central England temperature for the past few centuries is representative of central England and less so of Scotland". This is because different sites have different factors such as latitude, proximity to the sea, altitude, relief of the land, and exposure.

As a result, a critical comparison of the two records was undertaken, fulfilling a long-standing need for a comparison between the English and Scottish data (Lamb personal communication 1990).

COMPARABILITY OF THE ANNUAL TEMPERATURE RECORDS

Figure 1 shows a graph of the two datasets. The graph's most notable feature is the difference in mean annual temperature between the two temperature series. The mean temperature of Central England is 9.1°C, whereas the average temperature of Edinburgh is 8.3°C. Table 1 shows a comparison of the annual and seasonal temperatures of Central England and Edinburgh.

Also noteworthy (in Fig. 1) is the degree of agreement between the two temperature series. As Manley (1953) stated, "... even the short-term anomalies of temperature found in his English Midland data are also available in Mossman's series for Edinburgh". The correlation coefficient, or r value, for the two series is 0.80 – a strong correlation indeed.

Extreme values were considered in order to assess the similarity of the two series. Table 2 shows the method used in analysing the extreme values. First, the mean, $\overline{X}$, and standard deviation, SD, were calculated for each set. Second, an extreme value,

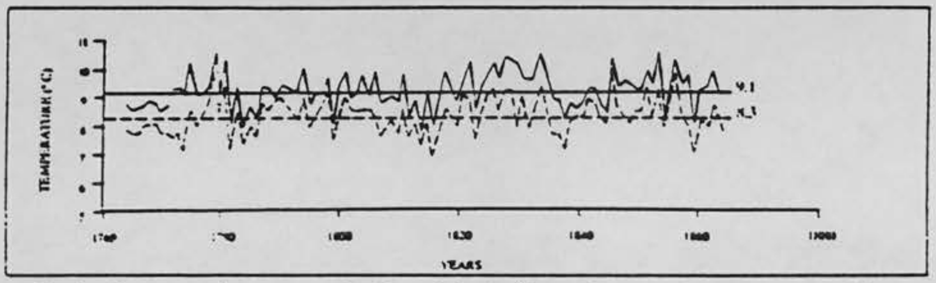

Fig. 1 Mean annual temperature for Central England (solid line) and Edinburgh (dashed line)

Table 1 A Comparison of annual and seasonal temperatures (°C) of Edinburgh and Central England

	ANNUAL	WINTER	SPRING	SUMMER	AUTUMN
Central England	9.1	3.6	8.1	15.2	9.4
Edinburgh	8.3	3.3	7.2	14.1	8.6
Mean difference	0.8	0.3	0.9	1.1	0.8
Difference between annual and seasonal mean difference		−0.5	+0.1	+0.3	0.0

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	$\overline{X}$	SD	$\overline{X}+1.5$ SD	$\overline{X}-1.5$ SD
Central England	9.0968	0.6226	10.0307	8.1629

Years with mean annual temperature >X+1.5 SD: 1775, 1779, 1781, 1822, 1826, 1828, 1831, 1834, 1846, 1857, 1869

Years with mean annual temperature <X−1.5 SD: 1782, 1799, 1814, 1816, 1838, 1855

	$\overline{X}$	SD	$\overline{X}+1.5$ SD	$\overline{X}-1.5$ SD
Edinburgh	8.2878	0.6099	9.2026	7.3729

Years with mean annual temperature >X+1.5 SD: 1779, 1781, 1826, 1834, 1846, 1852, 1857, 1868, 1893 – six years common with Central England

Years with mean annual temperature <X−1.5 SD: 1782, 1814, 1829, 1838 – three years common with Central England

$\overline{X}+1.5$ SD, was chosen. Since temperature is almost normally distributed, the choice of an extreme value is fairly arbitrary. Thus, the values of $\overline{X}+2$ SD or $\overline{X}+3$ SD could have been used; however, these values were not used because they failed to show clearly the similarity between the two records. Third, each year that was either $\overline{X}+1.5$ SD for warm years or $\overline{X}-1.5$ SD for cold years was found. Last, the years (with relevant SD) which were common or uncommon to both sets were found. Table 2 demonstrates that there is agreement between the two datasets. The relationship is, however, stronger in one direction; that is, if Edinburgh had a hot year, so too did England, whereas an English hot year was not necessarily matched in Scotland.

Although annually the English and Scottish data are comparable (albeit with a mean temperature difference of almost 1degC) so an investigation of the comparability between the two records for individual seasons was also undertaken.

SEASONAL COMPARABILITY

Figure 2 shows a graph of the two series for the winter season (December of the preceding year, January and February). The mean temperature for Central England was 3.6°C. The average Edinburgh winter temperature was 3.3°C. For the mean difference between the two datasets and the difference between the annual and seasonal mean, see Table 1. Figure 2 shows consistency between the graphs and reveals very strong agreement between the two records after 1851. The r value for winter temperature is 0.690. This is a relatively strong correlation; however, it is the smallest correlation of the four seasons.

Figure 3 depicts a graph of the Edinburgh and Central England datasets for the spring season (March, April and May). The mean temperature for Central England was 8.1°C. The average spring temperature for Edinburgh was 7.2°C. As can be seen, there is a high degree of consistency between the two series. The r value for the spring season is 0.751 – the strongest seasonal correlation.

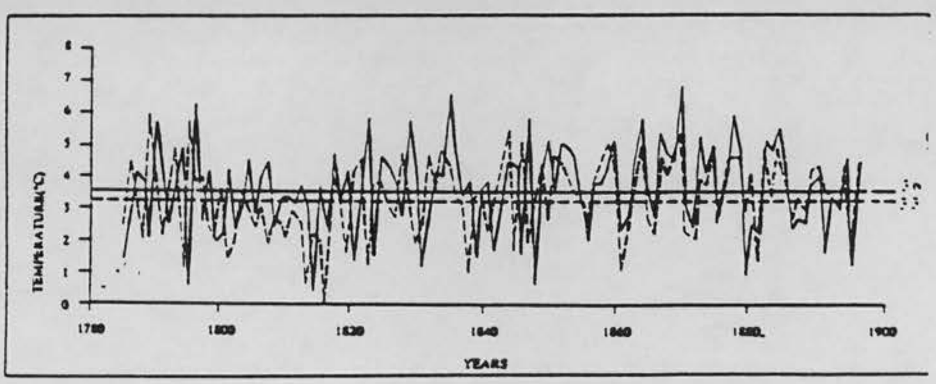

Fig. 2 Mean winter temperature (D,J,F) for Central England (solid line) and Edinburgh (dashed line)

Figure 4 is a graph of the English and Scottish temperature sets for the summer season (June, July and August). The mean temperature for Central England was 15.2°C. The average summer temperature for Edinburgh was 14.1°C. Figure 4 reveals considerable consistency between the two records. The r value is the second highest at 0.736.

Figure 5 displays a graph of Edinburgh's and Central England's mean autumn temperature (September, October and November). The mean autumn temperature for Central England was 9.4°C. Edinburgh's average autumn temperature was 8.6°C. Again, there is good consistency between the graphs. The correlation coefficient is 0.705.

Therefore, seasonally, there is strong agreement between the English and Scottish records: the correlation coefficients range from 0.690 to 0.751. Seasonally, the mean temperature of the two records differs by almost 1degC (as does the annual average tempera-

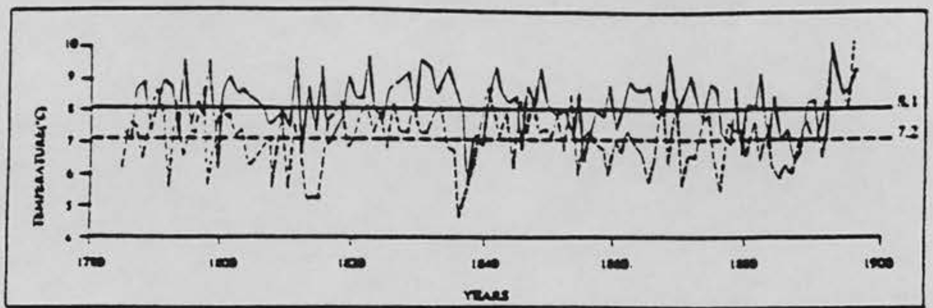

Fig. 3 Mean spring temperature (M.A.M) for Central England (solid line) and Edinburgh (dashed line)

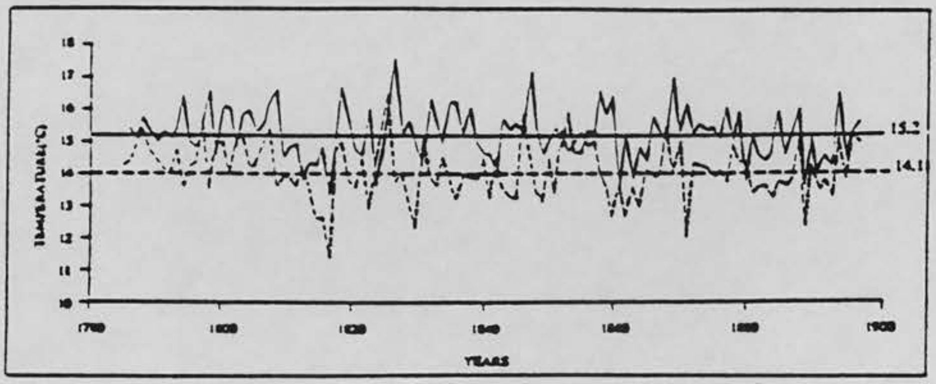

Fig. 4 Mean summer temperature (J.J.A) for Central England (solid line) and Edinburgh (dashed line)

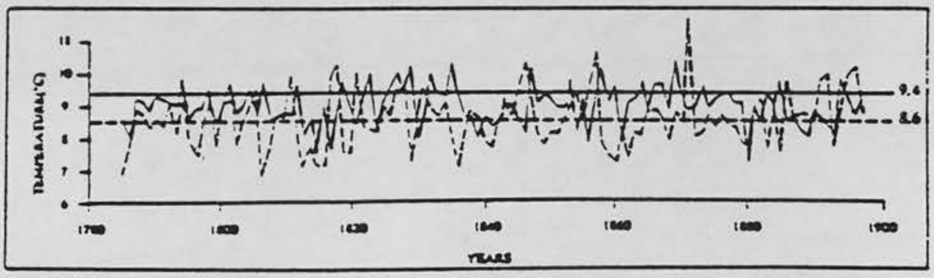

Fig. 5 Mean autumn temperature (S.O.N) for Central England (solid line) and Edinburgh (dashed line)

ture). In spring the series differ by 0.9degC and in autumn by 0.8degC. In summer the difference is greater than 1degC. Only in winter is the annual average difference not reached. These seasonal differences indicate a more continental type of climate in Central England compared with Edinburgh, with relatively colder winters and warmer summers in Central England.

APPLICATIONS

Because there is sufficient agreement between the two records (and because the difference in mean temperature remains fairly constant throughout the seasons), it is possible to use Manley's record and the mean annual difference in temperature between the two records (*i.e.* 0.8degC) to extend the Edinburgh record back in time. This technique (of subtracting 0.8degC from each of Manley's temperatures from 1763 back to 1659) would be especially valid for the period 1675–1704. At this time the North Atlantic was, on average, 4–5degC cooler than the 100-year mean of the period 1867–1970 (Lamb 1977). Therefore, the overall air temperature in the north-eastern half of Scotland would have been much lower than twentieth-century values in the last quarter of the seventeenth century than the temperature in England, as is shown by Manley's series (Lamb 1977).

A second application of the results is as follows. For the period prior to 1659, the only available temperature records are Lamb's overall trends in temperature. These, however, are less firmly established because they are based on interpretations of pressure conditions. The changes established for Central England are accepted by Lamb as being common to Scotland, and this study supports Lamb's assertion. It would seem reasonable to assume that this covariation also occurred in the past. However, it is important to remember that Edinburgh was already almost 1degC colder than Central England.

In addition, the results have important implications regarding the onset of growth in arable crops. Figure 6 displays a graph of the seasonal averages for the English and Scottish temperature sets. Two base temperatures, which relate to the commencement of growth in cereals, were selected; 6.0°C (the conventional temperature) and 4.4°C (Parry 1973). (Either value is equally valid. In fact, any value from 0°C to 6.0°C is now utilised in

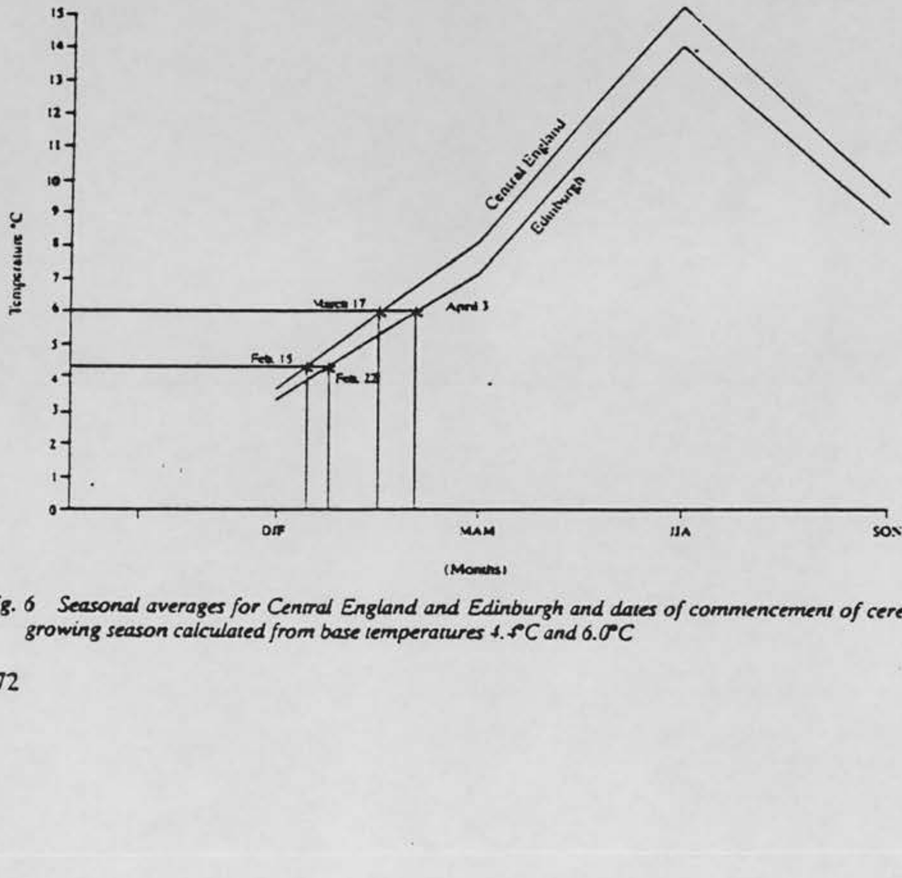

Fig. 6 Seasonal averages for Central England and Edinburgh and dates of commencement of cereal growing season calculated from base temperatures 4.4°C and 6.0°C

agrometeorological studies.) From the graph it can be seen that when the 4.4°C base temperature is applied, the growing season utilising English data may begin as early as 15 February, whereas the growing season using Scottish data may not begin until 22 February (a difference of one week). When the 6.0°C base is exercised, the growing season based on English data may commence on 17 March; however, the growing season in Scotland may not start until 3 April (a difference of two-and-a-half weeks). Therefore, if the Central England temperatures were employed to establish the date of the start of the growing season in Scotland, the proposed date would indeed be too early.

Lastly, the results may have significance for settlement distribution studies. The lapse rate for temperature in south-eastern Scotland is accepted as a fall of 1degC for every 82.4m. Edinburgh is on average 0.8degC cooler than Central England. If Central England data were employed to determine the height of agriculture and settlement, the actual elevation could be overestimated by 66m.

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